Technical/Regulatory Guideline

Technical and Regulatory Guidance Document for Constructed Treatment Wetlands

December 2003

Prepared by
The Interstate Technology & Regulatory Council
Wetlands Team

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EXECUTIVE SUMMARY

Constructed treatment wetlands are manmade wetlands built specifically to treat contaminants in surface water, groundwater, or waste streams such as leachate and acid mine drainage. The purpose of this document is to provide technical and regulatory guidance to help regulators, industry, consultants, and technology vendors understand, evaluate, and make informed decisions about the use of constructed treatment wetland systems. While there is extensive published literature on the subject, constructed wetland applications have generally been limited to the treatment of stormwater and municipal wastewaters. However, this technology is now emerging as a valid treatment option for a variety of waste streams, including acid mine water, remedial wastewaters, and agriculture waste streams. This guidance documents a number of current successful treatment systems, while it demonstrates the maturity of the technology in many emerging applications.

The document describes the fundamental mechanisms of wetland contaminant removal and overall wetland functions. Degradation mechanisms are described in more detail in *Phytotechnology Technical and Regulatory Guidance Document* (PHYTO-2), published in April 2001. The Wetlands Team's approach in this document is to provide both scientific accuracy and basic understanding of these mechanisms regardless of the regulatory authority overseeing the site or regulating the contaminant. Simply stated, the technology is mature and tested. It is now being used in new applications and in some cases on new contaminants. This guidance provides detailed descriptions of the various contaminant treatment objectives, treatment efficiencies, and goals of different constructed wetland applications. Detailed, site-specific predesign criteria and conceptual designs are outlined, followed by final design, postconstruction activities, operation and maintenance, monitoring, and implementation costs.

The document provides decision trees for each of the major constructed treatment wetland applications, designed to enable users to take basic information from a specific site and, through a flow chart, decide whether a particular wetland system is appropriate for the site.

There are regulatory issues affecting any remedial technology, and constructed wetland systems are no exception. Constructed treatment wetland discharges are normally regulated under the National Pollution Discharge Elimination System (NPDES). Many states have internal oversight of this program. The implementation of constructed treatment wetlands at a site generally encounters other regulatory issues with regard to performance, contingency plans, and potential ecological impacts. Some important considerations include

- use of nonnative, invasive, or noxious plants;
- clearly identifying the mechanism responsible for treatment;
- accounting for seasonal variability in system performance and maintenance requirements;
- determining the length of time to establish the wetland treatment system;
- documenting the expected future use of the site and deciding whether future use is compatible with sustaining the wetland or removing all traces of the wetland;
- removing mercury prior to wetland treatment or monitoring methyl mercury (Treatment of mercury in constructed wetlands can led to the production of methyl mercury, which may biomagnify in the food chain. Mercury should be removed prior to wetland treatment or methyl mercury monitored to avoid causing additional environmental problems.)

- determining ecotoxicity; and
- balancing water quality improvements with failure to meet regulatory standards. (At abandoned sites, constructed wetlands may improve water quality but not succeed in meeting meet strict numeric standards.)

Numerous case studies included in the document were selected to represent various constructed wetland systems and their various applications. These studies are under way, and contact information is provided so readers can follow up on continually progressing demonstrations and full-scale operations. Every effort was made to include detailed performance and cost information and a comparative evaluation against what may be considered more conventional techniques.

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FOR CONSTRUCTED TREATMENT WETLANDS

1.0 INTRODUCTION

Constructed treatment wetlands are manmade wetlands built to remove various types of pollutants that may be present in water that flows through them. They are constructed to recreate, to the extent possible, the structure and function of natural wetlands, which is to act as filters or "nature's kidneys." Wetlands are ideally suited to this role. They possess a rich microbial community in the sediment to effect the biochemical transformation of pollutants, they are biologically productive, and most importantly, they are self-sustaining. These factors make constructed treatment wetlands a very attractive option for water treatment compared to conventional systems, especially when lifetime operating costs are compared.

Constructed treatment wetlands (henceforth referred to merely as "constructed wetlands" unless otherwise differentiated) utilize many of the mechanisms of phytoremediation, though the maturity of wetland technology suggests that it is a discipline unto itself. While the published literature on constructed wetlands is extensive, many applications have been limited to the treatment of stormwater and municipal wastewater. However, the use of constructed wetlands is now emerging as a valid treatment technique for a variety of other waste streams. A list of the major general guidance documents relevant to the use of constructed wetlands as a water treatment technology is included in Reference/Resources at the end of this document.

The objective of this document is to present a systematic understanding of the technical and regulatory processes involved in the design and construction of constructed wetlands for treatment. Its use could maximize the number of successful systems. Further, this document demonstrates the maturity of the technology for applications such as stormwater and municipal wastewater treatment and further documents its importance in many emerging applications, such as mine drainage, industrial wastewaters, agricultural wastewaters, landfill effluent, on-site wastewater treatment, and remedial activities.

Constructed wetlands are primarily built to treat contaminated water, not to replace or mitigate habitat lost through development. This document will not describe "mitigation" wetlands, a topic reserved for a follow-on ITRC project; however, constructed treatment wetlands can offer valuable habitat. Where possible, the value of the habitat should be considered among net benefits when constructing any wetland.

Natural wetlands evolve, in part, in response to the chemical constituents in the water that flows through them. Water that flows over surfaces with sufficient velocity to dissolve substances or suspend solid particles eventually makes its way to receiving waters (lakes, ponds, oceans, etc.). In some areas of low hydraulic gradient, water velocity slows appreciably, and suspended solids settle out of the water column, forming a bed of sediments. These sediments are often rich in organic matter and soil nutrients, a favorable media for plant growth. Wetland plants, whose seeds are dispersed ubiquitously in soils, begin to grow in the sediments where water flows are quiescent and water depth is shallow enough to permit their emergence. The wetland plants, in

turn, remove dissolved contaminants such as nitrogenous compounds from the water and act to further decrease water velocity, resulting in increased sediment deposition.

Wetland protection regulations have mostly precluded the use of existing natural wetlands for treatment, though construction of artificial wetlands for water treatment is becoming an increasingly accepted practice. Because of their effectiveness and adaptability, constructed wetlands are used to improve the quality of discharges from various point and nonpoint sources. By careful design, contaminant removal mechanisms can be optimized to treat a particular contaminant type. Careful wetland design requires understanding of the fundamental mechanisms of both wetland function and treatment. Treatment wetlands are proficient and versatile in many applications. Unlike most treatment systems that focus on a single pollutant or pollutant class, wetlands use numerous interdependent, symbiotic processes for concurrent removal of several different pollutant classes. For example, a hydrophobic organic compound can sorb to a settling organic particle in the water column and, in turn, be biologically transformed into innocuous breakdown products.

Besides surface water treatment, constructed treatment wetlands can be used to treat saturated sediments such as dredge spoils (the reed-bed method) and even shallow groundwater in situ. Riparian buffer strips are a type of constructed wetland, and some vegetated swales that maintain saturated soil conditions for a long enough time to support characteristic wetland vegetation can also be considered treatment wetlands. There is a continuum of terrestrial phytoremediation systems grading into wetland systems. Where terrestrial becomes wetlands may provide treatment benefits above and beyond either system separately; and many hybrid systems are possible, using, for example, conventional free surface water wetlands transitioning into subsurface flow wetlands, and then into uplands.

The technology is adaptable to a variety of treatment needs through the selective design and use of various types of constructed wetlands in combination with other technologies, such as trickling filters. Constructed wetlands have significantly lower total lifetime costs and often lower capital costs than conventional treatment systems. Additionally, constructed wetlands

- tolerate fluctuations in flow and pollutant concentrations,
- provide flood protection,
- facilitate water reuse and recycling,
- can be built to fit harmoniously into the landscape,
- provide habitats for plants and wildlife,
- enhance aesthetics of open spaces,
- provide recreational and educational opportunities, and
- are an “environmentally sensitive” approach viewed favorably by the general public and regulatory agencies.

2.0 WETLAND CONTAMINANT REMOVAL

Constructed wetlands can treat contaminants such as total suspended solids (TSS), biochemical oxygen demand (BOD), organic compounds, and inorganic constituents to meet regulatory targets. Although the same wetlands can achieve multiple goals of contaminant removal, the mechanisms vary. Understanding the mechanisms and processes controlling contaminant removal increases the probability of success of the wetland application.

2.1 Wetland Characteristics

To understand the methods required in the design and construction of treatment wetlands and the processes by which constructed wetlands can remove pollutants, it is important to have a basic understanding of how natural wetlands work. Wetlands are generally characterized by the presence of three basic parameters—soils, hydrology, and vegetation. Water is usually present at the surface or within the root for extended periods of time. As a result of the saturated conditions that occur as a result of this water, soils present in wetlands develop certain unique conditions that are different from upland soils. Also, in response to the saturated conditions, wetlands support vegetative species that are adapted to living in wet conditions.

2.1.1 Soils

Soils consist of unconsolidated, natural material that supports or is capable of supporting plant life. The upper limit is air, and the lower limit is either bedrock or the limit of biological activity. Soils are generally divided into two different types—mineral and organic. Soils can be further categorized based on the amount of moisture present. Under wetland conditions, soils are considered to be hydric, i.e., saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper portion of the soil. Hydric soils are developed under conditions sufficiently wet to support vegetation typical to wet areas (hydrophytic vegetation).

A soil profile consists of various soil layers described from the surface downward. These layers, called soil horizons, are generally oriented approximately parallel to the soils surface. A soil horizon usually is differentiated from contiguous horizons by characteristics (e.g., color, structure, texture) that can be seen or measured in the field. Soil horizons can be divided into major classifications called master horizons. These master horizons are designated with the letters O, A, E, B, C, and R. The depth and content of these horizons vary greatly depending on the type and location of the soil.

The O horizon is a layer of soil dominated by organic material. Some of these soils are saturated with water for long periods or were once saturated but now drained, and some have never been saturated. The O layer often consists of undecomposed or partially decomposed leaf litter, mosses, lichens, and twigs that have been deposited on the surface. The A horizon, usually referred to as the surface soil or topsoil, is a layer under the O horizon in which organic material is being added. This horizon often has the characteristics of cultivation and other disturbances. Under the A horizon is the E layer, a mineral horizon in which the loss of silicate, clay, iron, aluminum, or a combination has resulted in a concentration of sand and silt. The E horizon is usually darker than the B horizon located below it. The B horizon is a zone of maximum

accumulation of materials from the A horizon. It is usually characterized by higher clay content and/or more pronounced soil structure development and lower organic matter than those of the A horizon.

Under the B horizon is the C horizon, consisting of unconsolidated parent material. In this horizon, the unconsolidated parent material has not been sufficiently weathered to exhibit characteristics of the B horizon. Clay content and degree of soil structure development in the C horizon are usually less than in the B horizon. The last major horizon, the R horizon, consists of consolidated bedrock.

Because of the saturation typical of wetland environments, soils tend to develop certain characteristics found only in wetlands. Again, these unique characteristics result from the influence of anaerobic conditions induced by permanent or periodic saturation. For example, anaerobic conditions result in a reducing environment, thereby lowering the reduction/oxidation (redox) potential for a soil. This condition results in the chemical reduction of some of the soil components, such as iron and manganese, leading to the development of soil colors indicative of wetland soils.

Other soil characteristics—such as high organic content, gleying, histic epipedons, sulfidic materials, aquic or peraquic moisture regime, and iron or manganese concretions—are also indications of a hydric soil condition. Gleyed soils develop when anaerobic soil conditions result in chemical reduction of iron, manganese, and other elements. This process results in characteristic bluish, greenish, or grayish colors. A histic epipedon is an 8- to 16-inch soil layer at or near the surface that is saturated with water for 30 consecutive days or more in most years and contains a minimum of 20% organic matter when no clay is present or a minimum of 30% organic matter when 60% or greater clay is present. Soils with histic epipedons are saturated for sufficient periods of time to prevent decomposition of the organic surface. An aquic or peraquic moisture regime is characterized by groundwater at the soil surface and soil totally free of dissolved oxygen. Iron or manganese concretions are elements that are sometimes segregated during oxidation-reduction processes.

The indicators described above cannot be applied to sandy soils due to their unique nature. Sandy soils are determined to be hydric based on the presence of high organic content in the surface horizon, vertical organic streaking in the lower horizons, or the presence of wet spodosols (deep organic layers at the typical water table).

2.1.2 Hydrology

"Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes" (Mitsch and Gosselink, 1986). It is the permanent or periodic saturation of a wetland area that results in the anaerobic conditions in the soil under which typical wetland biogeochemical processes occur. These processes cause the development of characteristic wetland soils, which support a dominant plant community adapted to living in saturated soils. The hydrologic state of a wetland can be represented by a hydrologic budget, which is essentially the difference between the amount of water moving into the wetland and the amount moving out. Wetland water budgets are

influenced by the balance between inflows and outflows of water; surface contours of the landscape; and subsurface soil, geology, and groundwater condition (Mitsch and Gosselink, 1986). A more detailed discussion of water budgets is included in Section 5.1, "Evaluation."

From a regulatory standpoint under the Clean Water Act, the hydrologic component of a wetland is present when inundation or saturation of the soil within 6–18 inches of the surface occurs for a minimum of seven consecutive days during the growing season. When inundation or saturation is not present, a number of characteristics (e.g., hummocking, aerial roots, oxidized roots, stained leaves, etc.) can be used to determine whether wetland hydrology exists.

2.1.3 Wetland Plants

Wetland ecosystems support plant communities dominated by species that are able to tolerate either permanent or periodic saturation. These hydrophytic species have adapted to environments that, for at least a portion of the growing season, are anaerobic. Additionally, plants in tidally influenced wetlands have adapted to salinity levels that would be toxic to other species. The distribution of vegetation within wetlands depends on the depth of water or length of saturation.

Wetland plants perform a number of important functions in wetlands. They serve to stabilize wetland soil and sediment and enhance the accretion of new sediments by the filtering action of their leaves and stems, causing settleable solids to fall out of the water column. They are the primary autotrophic organisms in these ecosystems, creating a biomass of reduced carbon compounds that serves as food for a variety of organisms, both micro- and macroscopic. Plants also have the ability to remove nutrients, trace elements, and organics from the water through biological uptake and surface adsorption.

During photosynthesis, plants consume carbon dioxide and release oxygen. Submerged aquatic plants growing within the water column raise the dissolved oxygen level in the wetland surface water and deplete the dissolved carbon dioxide, resulting in an increased pH. Rooted wetland macrophytes also actively transport oxygen from the atmosphere to the sediments. Some oxygen leaks from the root hairs into the rhizosphere, supporting aerobic and facultative anaerobic microorganisms in the otherwise anaerobic sediments and soils. Facultative anaerobic microorganisms are those that usually respire aerobically but can grow under anaerobic conditions.

Macrophytic plants are critical to high pollutant removal rates in treatment wetlands. Plants provide the necessary environment through oxygen and nutrient transfer to the sediments and soils and through their fixation of reduced carbon to support a diverse microbial population. Plants also release carbon compounds such as carbohydrates, which are products of photosynthesis that serve as a nutrient source for microbes that in turn may support other microbes. The result is a complex, synergistic system between numerous microorganisms for the degradation of a wide variety of contaminants. Thus, a complex web of interactions occurs between plants and the diverse community of microorganisms.

Plants control excess algal growth by intercepting sunlight. Algae are plants that release oxygen through photosynthesis. They are effective at removing nutrients from surface water. However,

excess algal growth within a constructed wetland can result in the release of undesirable levels of suspended solids and increased BOD levels to downstream receiving waters. A healthy stand of emergent vegetation obstructs sunlight from reaching the water surface and reduces the growth of undesirable algae.

Wetland ecosystems support plant communities dominated by species that are able to tolerate either permanent or periodic saturation. In general, plants can be divided into either herbaceous or woody vegetation. Herbaceous plants are those soft-stemmed plants devoid of woody tissue that often die back to the soil surface on an annual basis. Based on types of life forms, herbaceous wetland plants can be divided into those hydrophytes that are attached to the soil or sediment substrate and those that float free. Attached species include emergent species, floating-leaved plants, and submerged plants. Emergent plants are those species in which at least a portion of the foliage and all of the reproductive structures extend above the surface of any standing water. Typical of this type of plant include cattails (*Typha* sp.), rushes (*Juncus* sp.), and sedges (*Carex* sp.). Emergent species are usually found in shallow water or on saturated soils.

Floating-leaved plants have leaves that float on the surface of the water but are attached to the bottom by long stalks. These species are usually found in shallow-water habitats ranging from 12 to 40 inches. Typical of this type of plant are water lilies (*Nymphaea* sp.) and spatterdock (*Nuphar* sp.). Submerged plants are those species in which all foliage is found underwater. This includes eelgrass (*Zostera* sp.) and pondweed (*Potamogeton* sp.). Floating herbaceous hydrophytes are those species, such as duckweed (*Lemna* sp.), that float on the surface of the water and do not contact the underlying substrate.

Woody species are generally divided into either trees (greater than 20 feet tall) or shrubs (3–20 feet tall). Trees and shrubs are generally found on exposed, saturated soils, though in a few exceptions (bald cypress, *Taxodium distichum*) they can be found in standing water. Woody wetland species are generally characterized by physiological features, such as knees, adventitious roots, prop roots, expanded lenticels, and buttress swellings that allow for the interchange of oxygen in saturated, anaerobic conditions. Some of the more common wetland trees and shrubs include maples (*Acer* sp.), gums (*Nyssa* sp.), willows (*Salix* sp.), mangroves (*Rhizophora* sp.), and blueberry (*Vaccinium* sp.). While an important component of natural wetlands, woody species are not commonly used in treatment wetlands.

2.1.4 Wetland Classifications

Wetlands can be classified in a variety of ways. Historically, wetlands have been divided into freshwater and estuarine types (Mitsch and Gosselink, 1986; and Dennison and Berry, 1993). Freshwater wetlands were divided into swamps, bogs, marshes, and deep-water systems. Estuarine wetlands included tidal flats, salt marshes, and mangrove swamps. (See the Glossary for the definitions of these terms.)

One published system (Brinson, 1993) divides wetlands into a series of categories solely based on the geomorphic setting. These types include riverine, fringe, depressional, and peatland. This system is different from most others in that it does describe certain functions as part of the classification process.

Under Brinson's system, depressional wetlands are those located in a depression in the landscape, so that catchment area for surface runoff is generally small. Depressional wetlands are usually located at the headwater of a local drainage. Depressional wetlands include kettles, potholes, vernal pools, and Carolina bays. Riverine wetlands form as linear strips throughout the landscape along rivers, creeks, streams, and other moving bodies of water. Fringe wetlands occur in estuaries where tidal forces dominate or in lakes where water moves in and out of the wetlands from the effects of wind and waves. Peatlands are wetlands dominated by a peat substrate. These types of wetlands include blanket bogs and tussock tundra.

The most common means of characterizing wetlands is under the system developed by Cowardin et al., 1979: Wetland types can be put into five basic categories—marine, estuarine, riverine, lacustrine, and palustrine. The major categories or systems are based mostly on the hydrologic base for the wetlands. Each of these systems can be further broken down into subsystems, classes, subclasses, and dominance types based on the type of vegetation present and/or the bottom substrate for the wetland.

Marine wetlands include the open ocean overlying the continental shelf and the associated coastline. Estuarine wetlands consist of deepwater tidal flats and adjacent tidal wetlands, which are usually mostly enclosed by land but have at least sporadic access to the open ocean. The water associated with these wetlands is at least occasionally diluted by freshwater and generally extends from a point upstream where the salinity level is 5 parts per thousand to the seaward limit of wetland emergent species (Cowardin et al., 1979).

Riverine wetlands include all wetlands and deepwater habitats found within a river channel, with the exception of wetlands dominated by trees, shrubs, persistent emergent species, emergent mosses, and lichens. Palustrine wetlands include all nontidal wetlands dominated by trees, shrubs, persistent emergent species, emergent mosses, or lichens. Palustrine wetlands are bounded by uplands or any other type of wetlands and may be situated shoreward of lakes or river channels or in floodplains. Lacustrine wetlands include wetlands and deepwater habitats found in topographic depressions or dammed river channels, which lack trees, shrubs, emergent species, mosses, or lichen and exceed 20 acres in size. Riverine, palustrine, and lacustrine wetlands are all generally freshwater systems (Cowardin et al., 1979).

Constructed wetlands are typically categorized as marshes, though open water areas are often part of the treatment system.

2.2. General Pollutant Removal Mechanisms

Based on the functions and biogeochemical processes occurring within wetlands as a result of long-term saturation, constructed wetlands have the ability to remove or filter pollutants from water directed through them. Removal mechanisms can act uniquely, sequentially, or simultaneously on each contaminant group or species. As Figure 2-1 illustrates, processes taking place in a constructed wetland may be abiotic (physical/chemical) or biotic (microbial/phytological). The mechanisms used for treatment/removal of a contaminant depend on the specific contaminant, site conditions, remedial objectives, and regulatory issues.

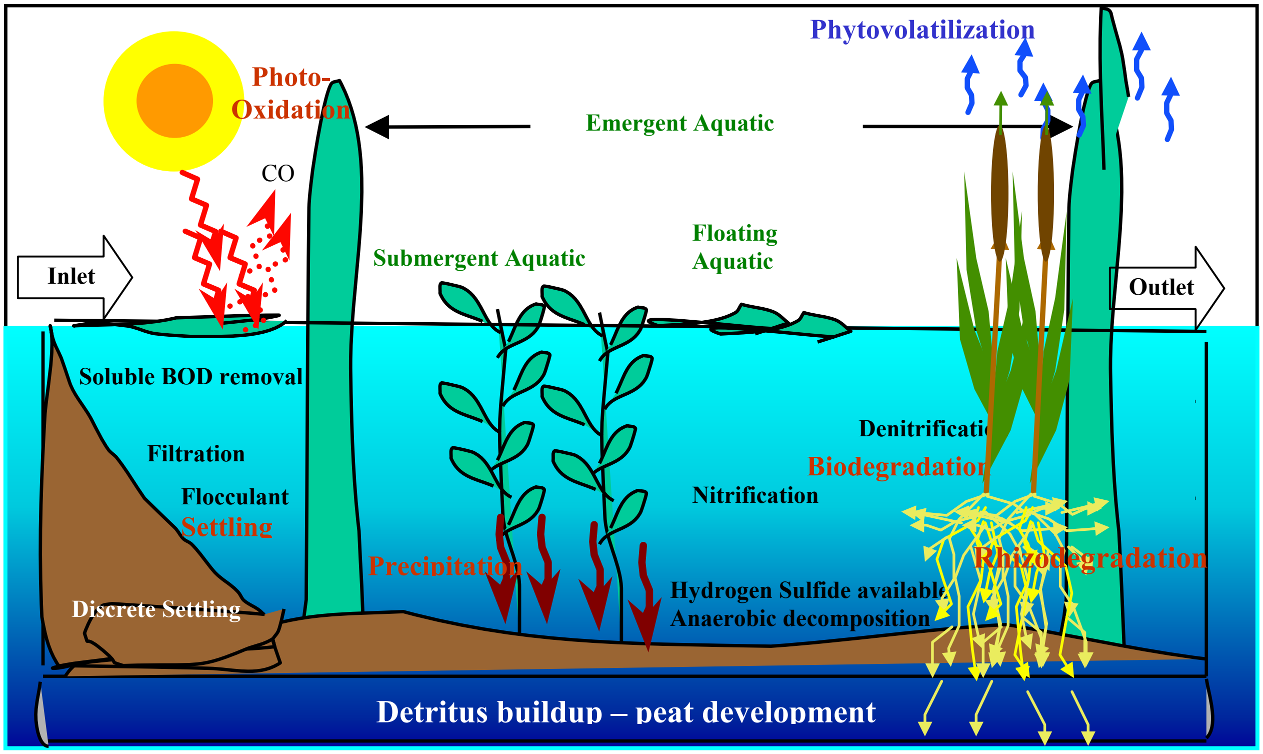

Figure 2-1. Processes Occurring in a Wetland

(Adapted from the course "Creating and Using Wetlands for Wastewater and Stormwater Treatment and Water Quality Improvement" at University of Wisconsin, Madison)

2.2.1 Abiotic

The primary physical and chemical processes that are responsible for contaminant removal in a constructed wetland include the following:

- settling, sedimentation
- sorption
- chemical oxidation/reduction—precipitation
- photodegradation/oxidation
- volatilization

Settling and sedimentation achieve efficient removal of particulate matter and suspended solids. The chemical process that results in short-term retention or long-term immobilization of contaminants is sorption. Sorption includes the combined processes of adsorption and absorption. Chemical precipitation involves the conversion of metals in the influent stream to an insoluble solid form that settles out. These reactions represent an effective means for immobilizing toxic metals in the wetland. Photodegradation involves the degradation/oxidation of compounds in the presence of sunlight. Volatilization occurs when compounds with significant vapor pressures partition to the gaseous state (see Figures 2-2 and 2-3).

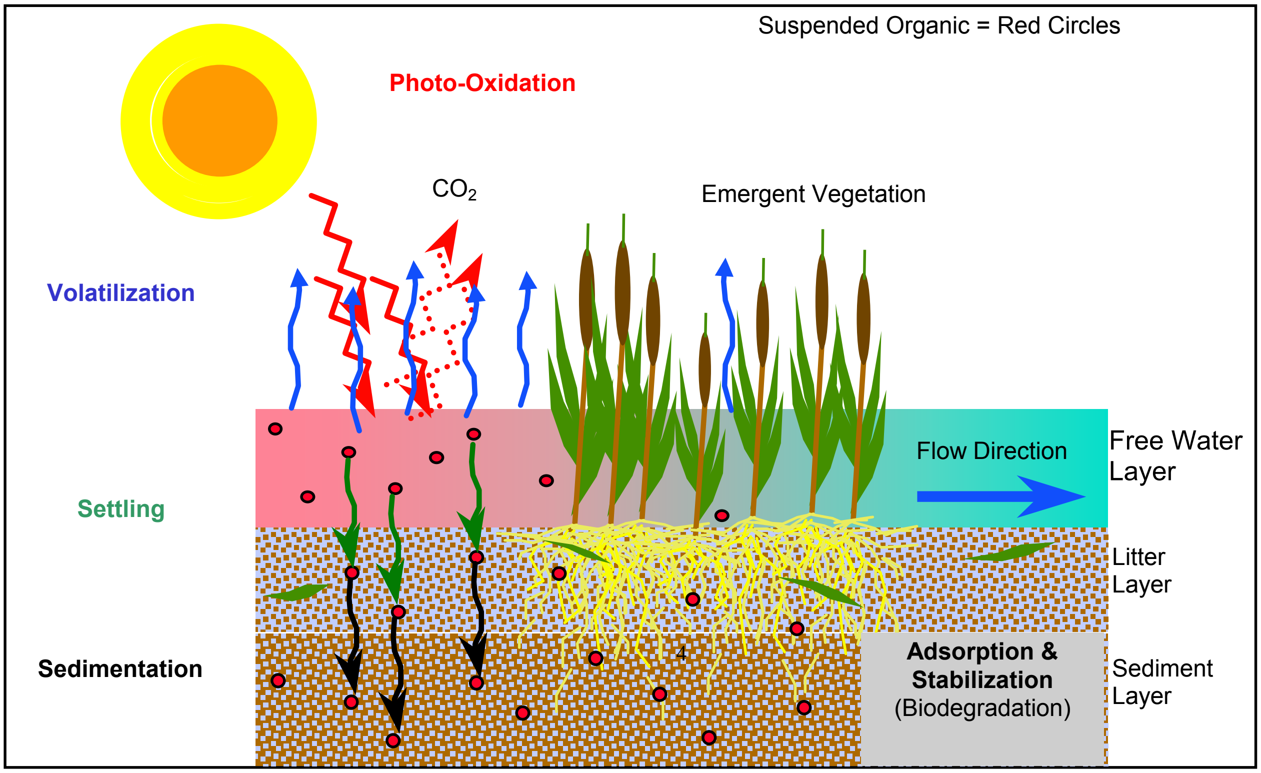

Figure 2-2. Abiotic Mechanisms Treating Organic Compounds in Wetland Treatment Systems

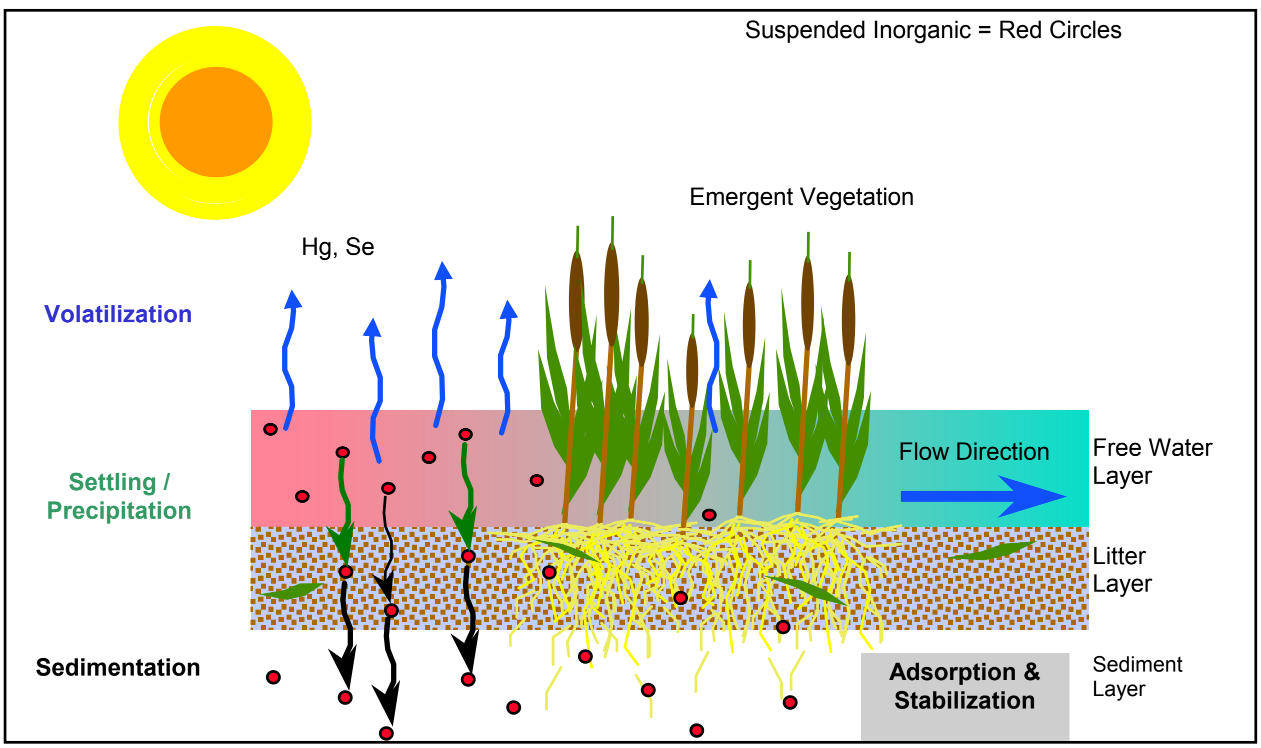

Figure 2-3. Abiotic Mechanisms Treating Inorganic Compounds in Wetland Treatment Systems

2.2.2 Biotic

In addition to the abiotic processes, biotic processes like biodegradation and plant uptake are major contributors for contaminant removal. Some microbial/phytological processes taking place in a wetland are given below:

- aerobic/anaerobic biodegradation
- phytoaccumulation/phytostabilization
- phytodegradation/rhizodegradation
- phytovolatilization/evapotranspiration

Metabolic processes of microorganisms play a significant role in removing organic compounds in aerobic/anaerobic environments of wetlands (see Figure 2-4). Plants either are responsible for direct uptake of contaminants that are required nutrients or—by rhizodegradation—provide exudates that enhance microbial degradation of organic compounds. Phytodegradation occurs when plant-produced enzymes break down the contaminants (organic and inorganic) that enter into the plant during transpiration. Phytoaccumulation is the uptake and accumulation of inorganic elements in the plants, and phytostabilization is the ability to sequester inorganic compounds in the root (see Figure 2-5). Phytovolatilization is the uptake and subsequent transpiration of volatile compounds through the leaves. Phytovolatilization may not be desirable in some cases since the contaminant is just transferred from one media (water) to another (air).

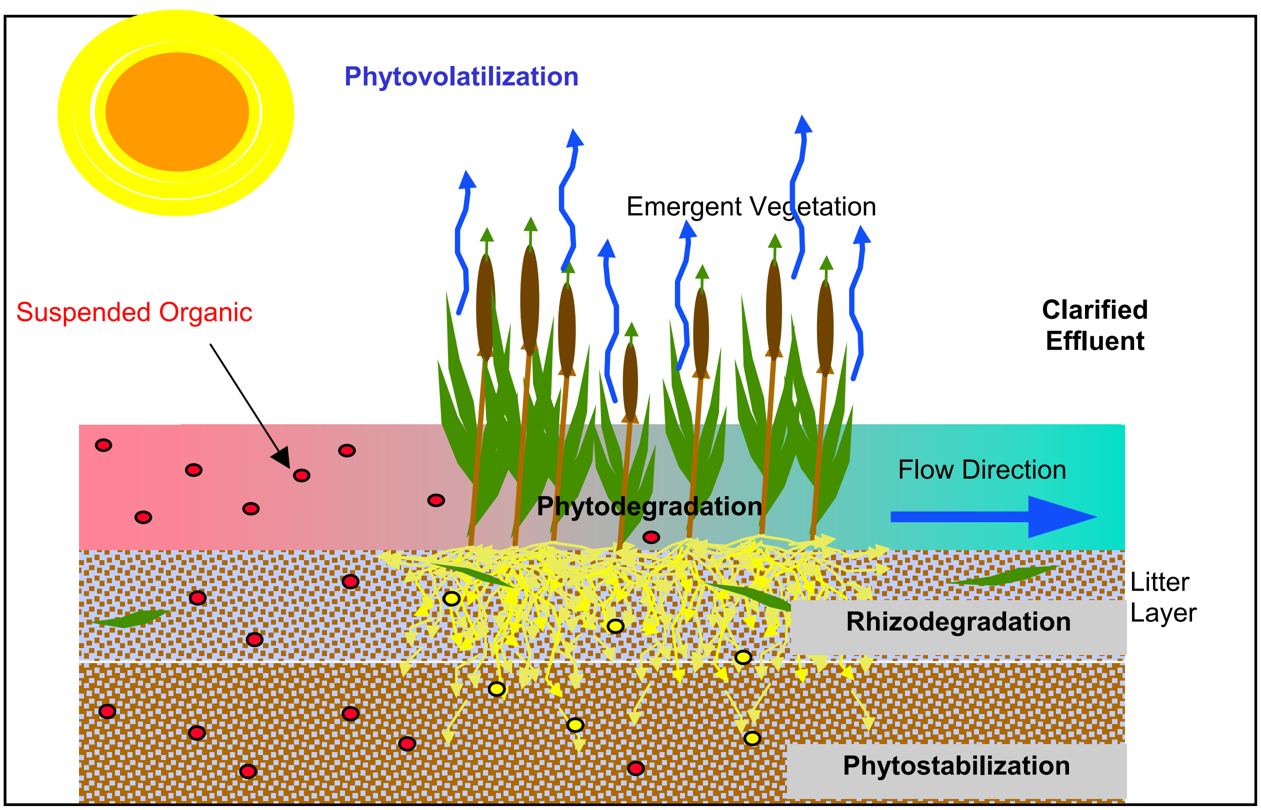

Figure 2-4. Biotic Mechanisms Treating Organic Compounds in Wetland Treatment Systems

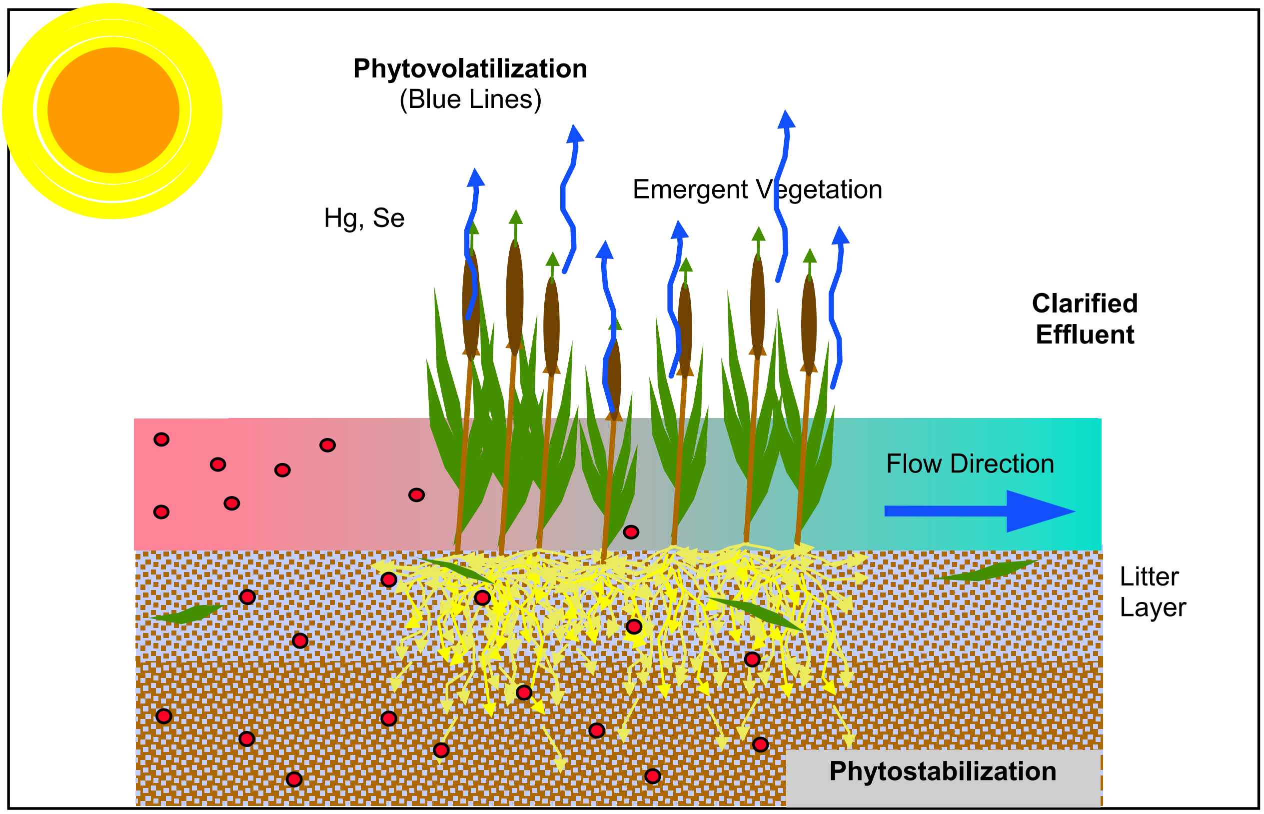

Figure 2-5. Biotic Mechanisms Treating Inorganic Compounds in Wetland Treatment Systems

Most pollutant-transforming chemical reactions occur in wetland water, detritus, and rooted soil zones. These transformations are a result of the high microbial activity that occurs in these soils. Biological removal mechanisms include aerobic microbial respiration, anaerobic microbial fermentation and methanogenesis, plant uptake, extracellular and intracellular enzymatic reactions, antibiotic excretion and microbial predation, and die-off.

High microbial activity is typical of wetland sediments due to the high rate of organic carbon fixations by wetland plants. The diverse microbial populations in the rooted soil zones, detritus layer, and submerged surfaces of plant leaves and stems are responsible for most pollutant transformations.

The flow of water in a wetland contacts the microbe (dense and porous litter layer) and—to a lesser extent—the sediment and soil, such that the organisms are given the opportunity to remove contaminants and use them as a nutrient source. Microbial diversity is supported by the gradation of aerobic to anaerobic zones in the litter, sediment, and soil layers. Each supports a unique, yet internally diverse, community of microorganisms. Even within the deeper anaerobic zones, there exist “micro-” aerobic zones (the rhizosphere) where anaerobic organisms can share metabolites with neighboring aerobic organisms. The symbiotic relationships between the plants and microbes are complex; plants and microbes often benefit one another, for instance, by exchanging nutrients or exudates.

2.3 Contaminant-Specific Removal Mechanisms

The dominant contaminant removal processes in wetlands are settling, biotransformation (microbial and plant-mediated), and plant uptake. Surface phenomena such as adsorption are also important. Combinations of complementary biological and nonbiological processes enable effective treatment of a wide range of contaminants. Contaminants that exhibit similar chemical and/or physical properties may be subject to the same removal mechanisms. Thus, contaminants can be placed into generic, mechanistic groups, depending on their chemical and physical properties. Table 2-1 summarizes some major groups of contaminants and their primary removal mechanisms in wetlands. Less significant mechanisms and secondary, tertiary, or ultimate fate processes are not included. Precursor processes are also not included.

Table 2-1. Primary Contaminant Removal Mechanisms

Contaminant Group or Water Quality Parameter	Physical	Chemical	Biological
Total suspended solids	Settling		Biodegradation
Oxygen demand • Biochemical oxygen demand • Chemical oxygen demand	Settling	Oxidation/	Biodegradation
Hydrocarbons • Fuels, oil and grease, alcohols, BTEX, TPH • PAHs, chlorinated and nonchlorinated solvents, pesticides, herbicides, insecticides	Diffusion/ volatilization Settling	Photochemical oxidation	Biodegradation/ phytodegradation/ phytovolatilization/ evapotranspiration
Nitrogenous Compounds • Organic N, NH_3, NH_4, NO_3^{-2}, NO_2^{-}	Settling		Biodenitrification-nitrification Plant uptake
Phosphoric Compounds • Organic P, PO_4^{-3}	Settling	Precipitation Adsorption	Microbes Plant uptake
Metals • Al, As, Cd, Cr, Cu, Fe, Pb, Mn, Ni, Se, Ag, Zn	Settling	Precipitation/ adsorption/ ion exchange	Biodegradation/ phytodegradation/ phytovolatilization
Pathogens		UV radiation	Die-off Microbes

(Sources: Kadlec and Knight, 1996; Hammer, 1997; Moshiri, 1993; Horner, 1995.)

2.3.1 Total Suspended Solids

Physical processes play an important role in contaminant reduction, especially for removal of inorganic and suspended solids. Gravitational settling is responsible for most of the removal of suspended solids. Gravity promotes settling by acting upon the relative density differences between suspended particles and water (see Figure 2-1). Efficiency of TSS removal is proportional to the particle settling velocity and length of the wetland. Wetlands promote sedimentation by decreased water velocity and the filtering effect of plant stems and leaves. While settling and sedimentation are often used interchangeably (Tchobanoglous and Burton, 1991), sedimentation referred to here represents physical compression and consolidation of settled solids in the detritus (litter layer). The compression is due to the ever-increasing mass of particles landing in this area. Although sedimentation is usually irreversible, resuspension may occur due to high water flow rate, wind-driven turbulence, bioturbation and gas lift (resulting from oxygen, methane, carbon dioxide production during photosynthesis, and organic matter decomposition).

2.3.2 Total Organic Carbon and Oxygen Demand

Wastewaters contain a wide variety of organic compounds, which are measured as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). The main routes for organic carbon removal include volatilization, photochemical oxidation, sedimentation, sorption, and biodegradation (see Figure 2-6). Organic contaminants sorbed onto particles flowing into the wetlands settle out in the quiescent water and are then broken down by the microbiota in the sediment layer.

Organic molecules are broken down by the microbiota by fermentation and aerobic/anaerobic respiration and mineralized as a source of energy or assimilated into biomass. The efficiency and rate of organic carbon degradation by microorganisms is highly variable and depends on the organic compound present in the influent. Volatilization may also be a significant removal mechanism in the microbial breakdown products of organics.

Organic matter contains about 45–50% carbon. BOD is a measure of the oxygen required by the microorganisms to oxidize the organic matter. Wastewater is high in organic matter and can be efficiently treated to regulatory levels using wetlands. A spectrum of reactions takes place in wetlands where carbon in the influent may be utilized. These include respiration in the aerobic zones and fermentation; methanogenesis; and sulfate, iron, and nitrate reduction in the anaerobic zones.

Respiration is conversion of carbohydrates to carbon dioxide, and fermentation is conversion of carbohydrates to lactic acid or ethanol and carbon dioxide. These microbial processes provide a biological mechanism for removal of organic compounds found in municipal wastewater, pesticides, and petroleum products. In a wetland, organic carbon is thus broken down into carbon dioxide/methane and/or is stored in plants, dead plant matter, microorganisms, or peat. Peat formation occurs when the rate of organic matter decomposition is lower than the rate of organic matter deposition. A significant part of BOD may be particulate and, therefore, susceptible to removal by particulate settling.

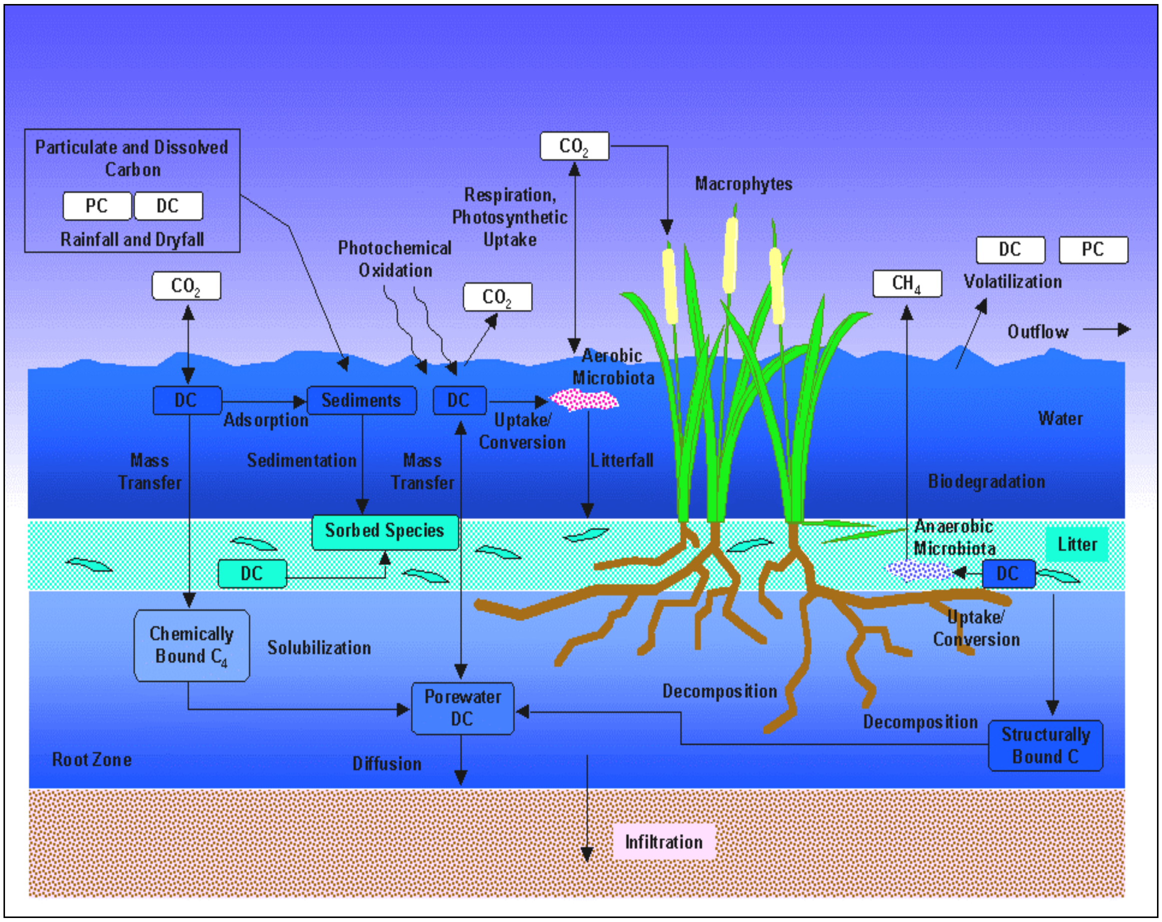

Figure 2-6. Mechanisms for Organic Compound Removal in Wetlands

2.3.3 Hydrocarbons

Hydrocarbons consist of a broad range of compounds, both naturally occurring and anthropogenically developed, whose characteristics are primarily determined by the arrangement of carbon and hydrogen compounds. Chemically, they can be divided into two very broad families—the aliphatics and the aromatics. Aliphatics can be further divided into three main groupings—the alkanes, the alkenes, and the cycloalkanes. Chemically, the aliphatic and aromatic compounds can be differentiated by the patterns of bonding between adjacent compounds.

Alkanes (both straight carbon chained and branched carbon chained) are simple compounds that are characterized by single carbon-carbon bonds. The more common alkanes include methane, butane, and propane and are seen as components of gasoline, JP-4 (jet fuel), diesel, and kerosene. Alkanes can be chlorinated (contain one or more chlorine atoms) to make a category of chemicals called volatile organic compounds (VOCs), which includes such common environmental pollutants as trichloroethylene, tetrachloroethylene, and vinyl chloride.

Alkenes have one or more double bonds between carbon atoms, while cycloalkanes are alkanes where the carbon atoms form a ring. Alkenes and cycloalkanes are found almost exclusively in gasoline and JP-4.

Aromatic compounds have one or more benzene rings as structural components to them. Benzene is a carbon ring that always consists of six carbons atoms and six hydrogen atoms (C_6H_6). The more common simple aromatics encountered as environmental pollutants include benzene, toluene, and xylene. A very common group of aromatic compounds is the polycyclic aromatic hydrocarbon (PAH) compounds, which occur as a result of chemical manufacturing or naturally in the environment as the result of organic degradation or incomplete combustion. Examples of these compounds include acenapththylene, acenaphthene, benzo(a)anthracene, fluorene, and pyrene.

The classes of compounds are susceptible (to varying degrees depending upon the chemical) to the degradation processes typical to constructed wetlands. However, there is little information on the ability of constructed wetlands to handle some of the more stable hydrocarbon compounds such as polychlorinated biphenyls (PCBs) or chlorinated pesticides such as DDT and dieldrin.

Kadlec and Knight (1996) indicate that the major routes for the removal of hydrocarbons via constructed wetlands are volatilization, photochemical oxidation, sedimentation, sorption, and biological or microbial degradation. Volatilization is the principal degradation pathway for the alkanes, while the aromatic compounds—likely to be more water soluble—tend to be acted upon by other processes upon dissolution in water. In general, high-molecular-weight compounds degrade more slowly than lower-molecular-weight compounds.

Biodegradation is one of the dominant hydrocarbon treatment mechanisms. Degradation occurs both aerobically and anaerobically, depending on the oxygen supply and the molecular structure of the compound. As oxygen is the most thermodynamically favored electron acceptor used by microbes in the degradation of organic carbon, rates of biodegradation of hydrocarbons in aerobic environments is more rapid than in anaerobic environments. However, the presence of other factors common to wetlands (nitrate, ferrous iron, and sulfate) that will serve as electron receptors during anaerobic biodegradation treat hydrocarbon compounds. Biodegradation in wetland environments can also address VOCs through a reductive dechlorination process. A typical flow would be in the reduction of tetrachloroethylene to trichloroethylene, dichloroethylene to vinyl chloride to ethene.

2.3.4 Nitrogen

Nitrogen, a major component of municipal wastewater, stormwater runoff, and industrial wastewater, is potentially toxic to aquatic organisms and plays a role in eutrophication. Nitrogen is an essential nutrient that may be removed through plant uptake. The ammonium and/or nitrate taken up by plants are stored in organic form in wetland vegetation. In addition to the physical translocation of nitrogen compounds in wetlands, the processes involved in nitrogen transformation are ammonification, nitrification, denitrification, nitrogen fixation, and nitrogen assimilation. Ammonification is the microbial conversion of organic nitrogen to ammonia. The energy released in this multistep, biochemical process is incorporated into the microbial biomass. Nitrification is a two-step, microbially mediated transformation of ammonia nitrogen to nitrate. Conversion of ammonium to nitrite by *Nitrosomonas* bacteria is followed by the oxidation of nitrite to nitrate by *Nitrobacter* bacteria. Removal of nitrate is by the biological process of

denitrification by *Bacillus, Enterobacter, Micrococcus, Pseudomonas, and Spirillum*. This bioprocess involves the conversion of nitrate to nitrogen gas, thus providing complete removal of inorganic nitrogen from the wetland. A simplified nitrogen cycle is depicted in Figure 2-7.

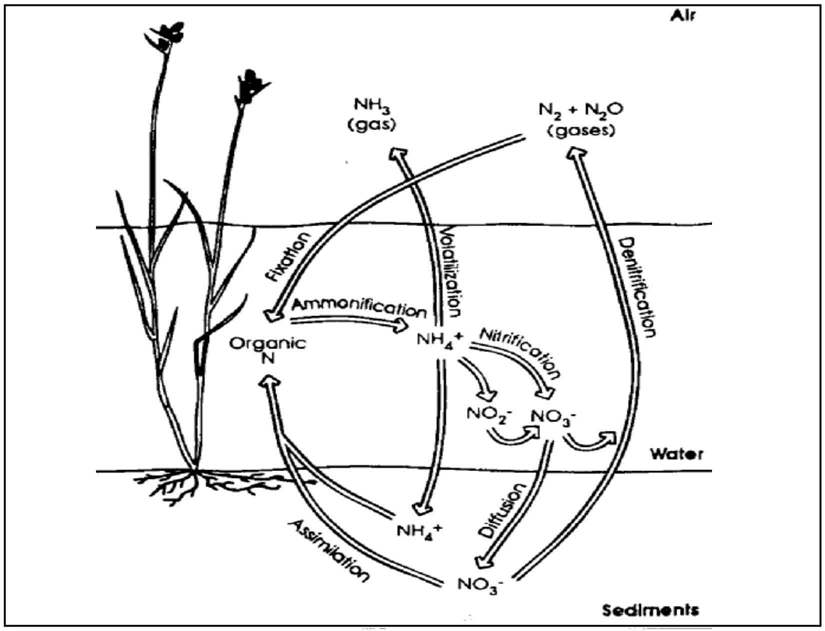

Figure 2-7. Nitrification Cycle

2.3.5 Phosphorous

Excess phosphorous in the influent can place a nutrient imbalance stress on the ecosystem. Like nitrogen, phosphorous is an essential macronutrient for growth of plants and organisms. Sedimentation of particulate phosphorous and sorption of soluble phosphorous are the two physical processes for phosphorous removal. Figure 2-8 shows phosphorous storage and transfer in a wetland environment.

Phosphine, a gaseous form of phosphorus, has been identified as a potential compound of significance in wetland environments (Gassman and Glindeman, 1993). Phosphine is soluble in water but has a high vapor pressure. It may be emitted from regions of extremely low redox potential, together with methane. As for the fate of phosphine in free air, the hydroxyl radical, which is one of the major reactive species in the atmosphere, reacts particularly rapidly with phosphine, as cited by Frank and Rippen (1987). They calculate that the half-life of phosphine in the atmosphere is about 28 hours, and on sunny days under conditions that allow a greater-than-usual production of hydroxyl radicals, phosphine's half-life may be as short as five hours. The final product of the reaction of phosphine with the hydroxyl radical is the phosphate ion, which falls to earth to carry on the global phosphorus biogeochemical cycle.

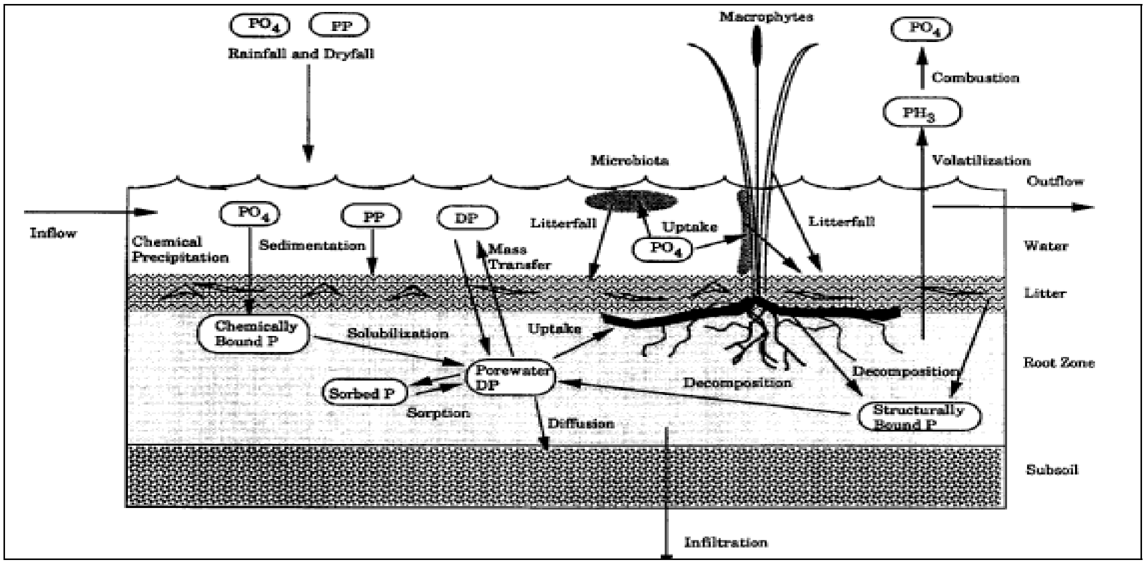

Figure 2-8. Phosphorus Storage and Transfers in the Wetland Environment
PO_4 = orthophosphate, PP = particulate phosphorus, DP = dissolved phosphorous, and PH_3 = phosphine. PP may consist of all forms shown in the root.

Devai et al. (1995) measured PH_3 emissions from a constructed wetland (1.0 hectares, phragmites and bulrushes) in Hungary and estimated that 1.7 g/m^2/year of phosphorous was being lost through this route. To date, all North American wetland phosphorus mass balance studies have ignored this possibility.

2.3.6 Metals

Metal contamination of soils and waters reported from around the world has a severe impact on environment and human health. Industrial and mining wastes are the most important sources of heavy metal environmental pollution (Quek and Forster, 1998). As reported by Hedin et al. (1994) and Sobolewski (1997, 1999), metal removal processes occurring in wetlands involve a series of mechanisms:

- filtration of solids,
- sorption onto organic matter,
- oxidation and hydrolysis,
- formation of carbonates,
- formation of insoluble sulfides,
- binding to iron and manganese oxides,
- reduction to nonmobile forms by bacterial activity, and
- biological methylation and volatilization of mercury.

See Table 2-2 for a summary of these mechanisms and efficiencies and Figure 2-9 for a graphical depiction of the mechanisms in the wetland system.

Table 2-2. Examples of Metals Removal in Wetland Treatment Systems

Metal	Removal %	Removal mechanism	Case study	References
Al	33	• Oxidation and hydrolysis	AMD Wetland, Kentucky (Fabius IMP1)	Edwards, 1993
	13		AMD Wetland, Kentucky (Widows Creek)	
As		• Formation of insoluble sulfides • Binding to iron and manganese oxides		
Cd	98.7	• Formation of insoluble sulfides • Filtration of solids and colloids	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	75		Bulrushes in gravel	Sinicrope et al., 1992
	79		SSF wetlands	
	99.7		SF cattail	Noller, Woods, and Ross, 1994
Cr	87.5	• Reduction to non-mobile form by bacterial activity	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	40		Freshwater marsh receiving urban stormwater, Orlando, FL	Schiffer, 1989
	84		Bulrushes in gravel	Sinicrope et al., 1992
	68		SSF wetland	
	>65		Retention basin, bulrush SF Cells, hydrosoils supplemented w/ gypsum	Nelson et al., 2002 Gladden et al., 2003
Cu	96	• Sorption onto organic matter • Formation of insoluble sulfides • Binding to iron and manganese oxides • Reduction to non-mobile form by bacterial activity	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	87.5		Freshwater marsh receiving urban stormwater, Orlando, FL	Schiffer, 1989
	70.1		Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH^{2}M Hill, 1992
	88		SSF Wetland	Sinicrope et al., 1992
	36		Typha SF	
Fe	66.7	• Oxidation and hydrolysis • Formation of carbonates • Binding to iron and manganese oxides	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	58.2		Average for 137-AMD constructed wetlands	Wieder, 1989
	98		AMD wetland, KY (Fabius IMP1)	Edwards, 1993
	97		AMD wetland, KY (Widows Creek)	

Metal	Removal %	Removal mechanism	Case study	References
	9		Natural wetland, TN	
Pb	83.3	• Formation of insoluble sulfides • Filtration of solids and colloids • Binding to iron and manganese oxides	Freshwater marsh receiving urban stormwater, Orlando, FL	Schiffer, 1989
	26		AMD wetland, KY (Widows Creek)	Edwards, 1993
	86		Bulrushes in gravel	Sinicrope et al., 1992
	98		Typha SF	Noller, Woods, and Ross, 1994
	94		Typha/Melaleuca SF	
Mn	43	• Oxidation and hydrolysis • Formation of carbonates • Binding to iron and manganese oxides	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	79		AMD wetland, KY (Fabius IMP1)	Edwards, 1993
	40		Natural wetland, TN	
	98		Typha SF	Noller, Woods, and Ross, 1994
	75		Typha/Melaleuca SF	
Ni	70.7	• Sorption onto organic matter • Formation of carbonates • Binding to iron and manganese oxides	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	25		Freshwater marsh receiving urban stormwater, Orlando, FL	Schiffer, 1989
	47		Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH^{2}M Hill, 1992
	63		Bulrushes in gravel	Sinicrope et al., 1992
	90		Typha/Melaleuca SF	Noller, Woods, and Ross, 1994
Se	-	• Reduction to non-mobile form by bacterial activity • Volatilization		Adriano, 2001
Ag	75.9	• Formation of insoluble sulfides • Filtration of solids and colloids	Cypress-gum swamp receiving municipal effluent, Conway, SC	CH^{2}M Hill, 1991
Zn	89.5	• Formation of insoluble sulfides • Filtration of solids and colloids • Binding to iron and manganese oxides	Constructed meadow/marsh/pond, Brookhaven, NY	Hendrey et al., 1979
	66.7		Freshwater marsh receiving urban stormwater, Orlando, FL	Schiffer, 1989
	73		Carolina bay receiving municipal effluent, Myrtle Beach, SC	CH^{2}M Hill, 1992
	33		AMD wetland, KY (Widows Creek)	Edwards, 1993

Metal	Removal %	Removal mechanism	Case study	References
	79		Bulrushes in gravel	Sinicrope et al., 1992
	96		Typha/Melaleuca SF	Noller, Woods, and Ross 1994
	98			
Hg	85 whole system & 75 wetlands	Sorption to organics/silts with possible immobilization as sulfides	Constructed wetland: storm water retention basin & 8 acre bulrush wetland cells; hydrosols supplemented w/ gypsum	Nelson et al., 2002 Gladden et al., 2003

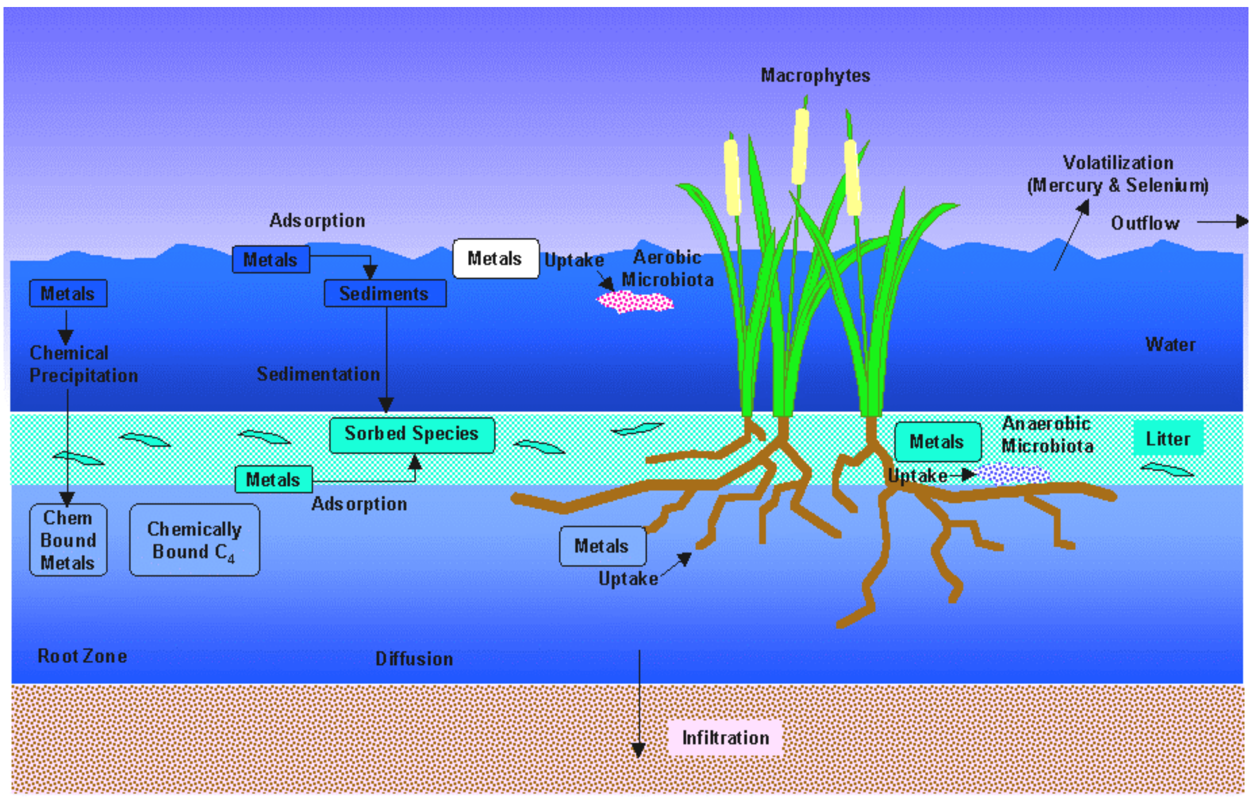

Figure 2-9. Mechanisms of Metals Removal in Wetlands

Filtration of Metals Suspended on Solids

Contaminated waste streams may contain suspended solids including adsorbed metals, which are easily filtered and retained in wetlands. Such processes can be important for mine drainage or for alkaline effluents.

Sorption of Metals onto Organic Matter

It is well documented (Kadlec and Keoleian, 1986; Drever, 1988) that several metals (e.g., Cu, U, and Ni) have a high affinity to bind to organic matter. The interactions are mediated by the

carboxyl and phenolic hydroxyl groups from organic matter, e.g., humic acids (Tipping and Hurley, 1992) with the formation of stable complexes.

Organic matter is abundant in wetland systems, particularly in the detritus layer. Moreover, constructed wetlands may be designed in such way that they will mimic the organic matter loading of natural mature wetlands by using an organic substrate such as peat (Sobolewski, 1999). The problem with this removal mechanism is that organic matter is subjected to biodegradation and may eventually release the adsorbed metals following decomposition. Several studies (Boyle, 1965; Berner, 1980) have shown that there are alternatives that will prevent the release of metals, including an aging phenomenon (responsible for formation of colloidal complexes) and the formation of insoluble sulfides.

Oxidation and Hydrolysis of Metals

Aluminum, iron, and manganese can form insoluble compounds through hydrolysis and/or oxidation that occur in wetlands. The result is the formation of a variety of oxides, oxyhydroxides, and hydroxides (Karathanasis and Thompson, 1995). Oxidation and/or hydrolysis are generally the main processes responsible for removal of these metals from contaminated streams:

- Al solubility is purely governed by pH (Hedin, Nairn, and Kleinmann, 1994). To remove aluminum, a wetland should increase water pH to 5 and provide sufficient retention for subsequent precipitation of aluminum hydroxides.

- Fe removal depends on pH, oxidation-reduction potential (ORP), and the presence of various anions, for example carbonates and sulfides. Ferric iron (Fe^{3+}) behaves similarly to aluminum and may be removed by simply increasing pH to 3.5 with sufficient retention. Ferrous iron (Fe^{2+}) should first be oxidized to ferric iron; otherwise it is highly soluble in waters that have low dissolved oxygen and a pH up to 8. At pH less than 4 or 5, bacteria are mainly responsible for the catalytic process that oxidizes ferrous to ferric iron (Robbins and Norden, 1994). At pH 6 and above, abiotic oxidation is the primary removal process. Fe removal from wetlands was reported by Stark et al. (1994) to be nearly 100% after 8 years of operation.

- Manganese removal is the most difficult to achieve since its oxidation proceeds slowly in aerobic wetlands and at a pH less than 8 (Stumm and Morgan, 1981). Additionally, manganese precipitates will return to solution in the presence of ferrous iron. Bacteria play an important role in the oxidation of Mn since they accelerate the oxidation of Mn^{+2} to Mn^{+4}. Decreasing temperature in winter reduces microbial activity, and removal may decrease.

Formation of Metal Carbonates

Metals may form carbonates when ambient concentrations of bicarbonate in water are high. Carbonates are less stable than sulfides but still can play an important role in the initial trapping of metals. These compounds may be transformed to more geochemically stable forms following the initial carbonate formation.

There are very few cases of wetlands retaining significant amounts of carbonates (Hambley, 1996). Carbonate formation can take place if limestone occurs in the flow path of mine drainage or when bacterial production of bicarbonate alkalinity in wetland sediments is substantial. Significant quantities of Cu and Mn carbonates accumulated in some natural wetlands (Sobolewski, 1999). At the Birchtree Mine, the mine drainage contained elevated sulfates, but approximately 45% of the nickel removal in a wetland was due to carbonate formation (Hambley, 1996). Siderite forms when iron oxyhydroxides are reduced during the decomposition of organic matter (Virtanen, 1994).

Formation of Insoluble Metal Sulfides

Wetlands provide anaerobic conditions that promote the growth of sulfate-reducing bacteria. In mine drainage waters rich in sulfates, these bacteria will generate hydrogen sulfide. Most transition metals react with hydrogen sulfide to form highly insoluble sulfides (Stumm and Morgan, 1981). The organic-rich detritus of wetlands treating mine drainage water positively influences sulfate reduction.

Metals such as Ag, Cd, Hg, As, Cu, Pb, and Zn form highly insoluble sulfide compounds in contact with low concentrations of hydrogen sulfide. Sulfide minerals have been reported in a number of wetland sediments (Sobolewski, 1999). The formation of metal sulfides and production of alkalinity follows seasonal patterns in wetlands located in northern climates.

Binding of Metals to Iron and Manganese Oxides

Metals may become associated with iron and manganese oxides (Stumm and Morgan, 1981; Drever, 1988) as a result of the adsorption or co-precipitation phenomena. The process is presumed not to be important in the long-term removal and retention of metals because iron and manganese oxides, being redox sensitive, may redissolve following changes in oxygen concentration.

Waters treated in wetlands may be rich in iron and manganese, which will precipitate as oxides, oxyhydroxides, or hydroxides in the oxidizing environment at the wetland surface. For example, Cu, Fe, Mn, Ni, Co, Pb, U, and Zn that were retained in wetlands in Northern Australia were mostly associated with iron oxides (Noller, Woods, and Ross, 1994). These metals have shown no sign of dissolution from the wetland (Eapaea, Parry, and Noller, 1995). A natural wetland in North Wales, England was reported to effectively retain metals such as As, Co, Ni, and Zn in association with iron oxides (Horsnail, Nichol, and Webb, 1969). In addition, As and Zn were reported to be retained on iron plaques at the surface of plant roots (Otte, Kearns, and Doyle, 1995).

Reduction of Metals to Nonmobile Forms by Bacterial Activity

In wetland systems, some metals (Cr, Cu, Se, and U) can be reduced into nonmobile forms (e.g., metallic forms) by processes that are governed by factors such as Eh-pH and sulfide concentrations (sulfide minerals will form at high concentrations). Metals such as Cu, Se, Cr,

and U may be reduced into nonmobile forms in some wetlands (Sobolewski, 1999). Native Cu was reported to accumulate only in slightly acidic wetlands (Boyle, 1977). Selenium has been shown to accumulate in natural wetlands where its soluble oxyanion is reduced to elemental Se, which is insoluble (Oremland, 1994). Selenate-reducing bacteria also play an important role in Se reduction. A form of iron with an oxidation state intermediate between III and II (commonly called "green rust") induces the reduction of Se. In the case of Se accumulation, ecotoxicological effects should be considered. Cr and U become immobilized when reduced through processes biologically catalyzed by microorganisms (Fude et al., 1994) or chemically by hydrogen sulfide.

Biological Methylation and Volatilization of Mercury

Most metals can be effectively retained in wetlands through a series of physical, chemical, and biological processes. Sustainable metal uptake occurs primarily in the wetland sediments. However, mercury, the most unique of the heavy metals in wastewaters, is an exception.

In nature, mercury (Hg) exists in three principal forms. Elemental mercury [Hg(0)] exhibits low reactivity unless first oxidized to Hg(II) by peroxidase or catalase and has a relatively short residence time. Mercuric mercury [Hg(II)] is reactive but inefficiently absorbed through the gastrointestinal tract. Methyl mercury (Me-Hg) is reactive, highly mobile, and efficiently absorbed through the gastrointestinal tract and biomagnifies through the food chain. The most common forms of Hg in oxidizing aquatic systems are mercuric salts, such as $HgCl_2$ (inorganic Hg) and complexes with dissolved organic matter. Under reducing conditions, mercury forms precipitates with sulfides (HgS). However, in wetland systems, under anaerobic sediment conditions, mercuric ions are biomethylated by a series of anaerobic microorganisms to methyl (mono- and dimethyl) mercury.

Methyl mercury is a serious problem in aquatic ecosystems as it readily biomagnifies in the food chain and is highly toxic. When the effluent to be treated contains Hg, it is likely that some of the Hg will be transformed within wetland systems to methylated forms, thereby creating additional environmental problems. Experimental data to date indicates low removal rates of mercury in some natural wetlands receiving municipal effluent (Kadlec and Knight, 1996).

At the DOE Savannah River Site, an eight-acre wetland treatment system has been constructed to remove copper and mercury from an industrial discharge. The wetland was planted in giant bulrush, and the soil was amended with gypsum to provide an additional source of sulfate for reduction. Mercury removal from the waters has averaged about 85% for water entering an upstream retention basin, which is part of the system, and about 75% for water through the wetland cells alone (Nelson et al., 2002; Gladden et al., 2003). Removal efficiency increased during the second year of operation with input concentrations at the retention basin and wetland cells averaging 64 and 35ng /L, respectively, while discharge concentrations from the system averaged about 8 ng/L. Methyl mercury concentrations were low, averaging about 5–6% of the total mercury content of the discharge water and never exceeding 10% of the outflow concentration. Maximum methyl mercury concentrations were measured in July, and related mesocosm-level research suggests that this increase may be related to the translocation and release of carbon compounds from the plant roots to the soil, thereby stimulating the bacteria responsible for mercury methylation (Harmon, 2003).

Despite mercury removal under certain environmental conditions, any methyl mercury production is undesirable. As a result, wetlands are generally not recommended for treatment of elevated levels of mercury unless pilot studies have demonstrated that methyl mercury production is within acceptable limits.

3.0 TYPES OF CONSTRUCTED WETLAND SYSTEMS

The two main types of constructed wetlands are surface flow (SF) and subsurface flow (SSF). SF systems outnumber SSF systems in the United States by over two to one (USEPA, 1993), though in Europe the reverse is true. In general, SF wetlands require more land than SSF wetlands for the same pollution reduction but are easier and cheaper to design and build. SSF systems are often more efficient but can cost significantly more than equivalent SF wetlands; however, recent data may show efficiencies are more equitable (Kadlec, 2002, personal communication). In Europe, many small treatment wetlands have been implemented for treatment of residential wastewater, for which SSF wetlands have several advantages, particularly in regard to the limited exposure pathway of pathogenic microbes and other contaminants. SSF wetlands hold promise for treatment of industrial effluents or other wastewaters containing hazardous contaminants due to SSF wetlands' inherent exposure-limiting characteristic. The two types of wetlands are further described in the following sections.

3.1 Surface Flow Wetlands

SF wetlands consist of shallow basins in soil or any other media that will support plant roots. Reed and Brown (1992) characterize this wetland as most closely mimicking natural marshes. An SF wetland generally has a soil bottom, emergent vegetation, and a water surface exposed to the atmosphere. The water surface moves through the wetland above the substrate at low velocities in a quiescent manner. Areas of open water may or may not be incorporated into the design.

Plants in these SF systems are able to withstand continuously saturated soil conditions and the corresponding anaerobic soils. SF wetlands have variable oxygen levels depending on atmospheric diffusion, wind action, and the amount of algae or macrophytes available to introduce oxygen to the system. Dissolved oxygen levels are at their highest at the air/water interface and decrease with depth. Depending upon the depth of the water and its quiescence, dissolved oxygen levels may be quite low at the bottom of the water column and even anaerobic just a few millimeters below the water/sediment interface.

SF wetlands are generally the least costly to construct (on a per acre basis), simplest to design, and provide the most valuable type of habitat. SF wetlands offer greater flow control and diversity in design and purpose than SSF wetlands. Additionally, SF wetlands have greater aesthetic appeal, wildlife habitat availability, and recreational opportunities, which foster public support.

One type of SF constructed wetland design is the marsh system, which generally has a large surface area and uses areas of shallow water to support wetland plants. As shown in Figure 3.1, some designs have two small pools, each several feet deep, located near the inlet and outlet. The inlet pool, or forebay, quickly reduces incoming water velocity to promote settling. Most of the sediment loading occurs in the forebay, so maintenance removal of sediments, if necessary, should be needed only in this localized area. The micro-pool prior to the discharge point affords hydraulic depth and flow control and can contribute to storage during extreme flows. The overall shape and placement of plants and pools vary widely and can contribute to storage during

extreme flows. In certain circumstances, groundwater flow may be used to augment water levels in areas of shallow water tables.

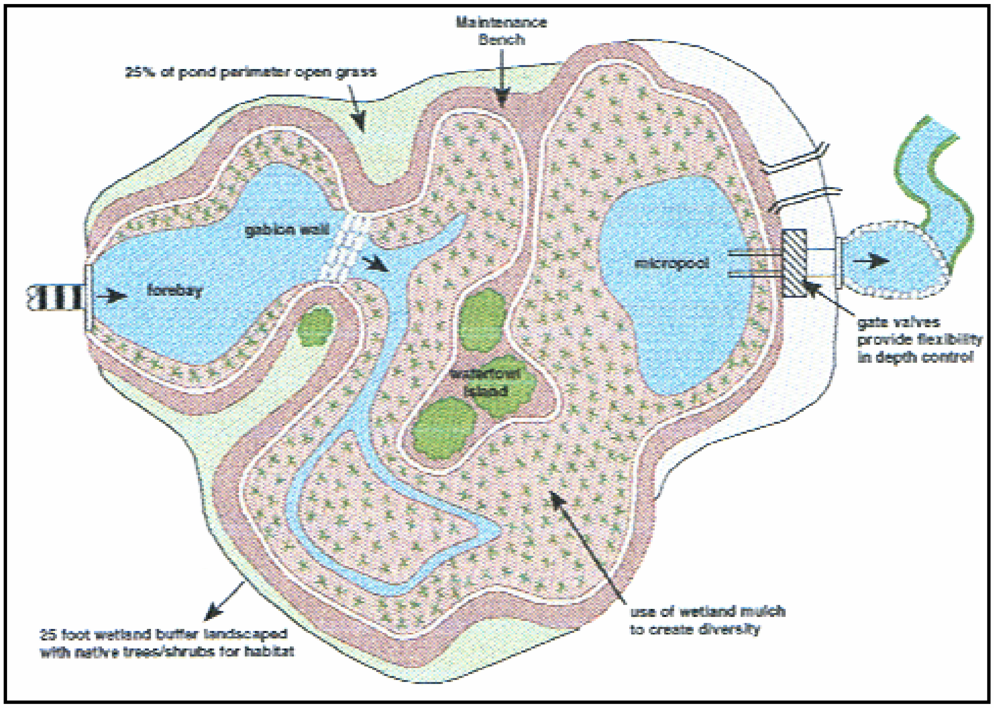

Figure 3-1. Marsh-Type SF Wetlands
(Figure Provided by the New Jersey Department of Environmental Protection)

A pond wetland system is very similar to the marsh design but with the added benefits of relatively deep ponds instead of forebays (see Figure 3-2). Typical pond depths are 6–8 feet (Horner, 1995). Different types of ponds can be used, depending on project needs. An anaerobic pond, located prior to the wetland, can be used for treatment of soluble organic matter, effluent from secondary treatment, and nutrients. Facultative ponds are useful for pretreatment of primary effluent or certain industrial wastes (Tchobanoglous and Burton, 1991) .The pools can provide considerable storage for applications such as stormwater runoff treatment. Finally, since the ponds are situated before the wetlands, they accumulate most settleable solids, thereby confining maintenance cleaning to the pond area only.

3.2 Subsurface Flow Wetlands

Also known as reed beds, rock-reed filters, gravel beds, vegetated submerged beds, and the root method, SSF wetlands are generally constructed with a porous material such as soil, sand, or gravel for a substrate. Reed beds and rock-reed filters use sand, gravel, or rock as substrates, while the root method uses soil. They are designed so that water flows below ground surface through the substrate.

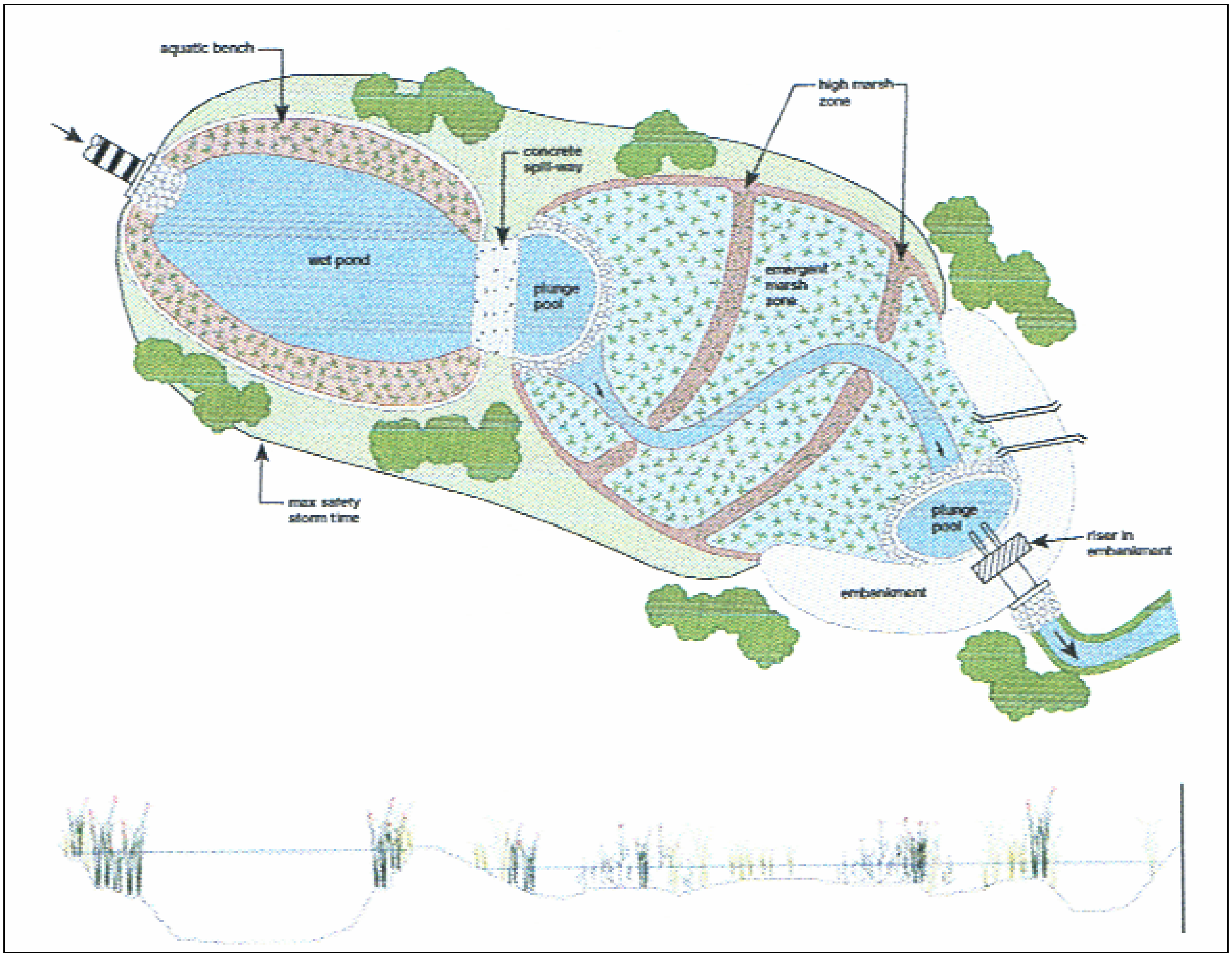

Figure 3-2. Pond-Type SF Wetland
(Figure provided by the New Jersey Department of Environmental Protection)

The advantages of SSF systems include increased treatment efficiencies, fewer pest problems, reduced risk of exposing humans or wildlife to toxics, decreased waterfowl use (advantageous near certain facilities such as airports), and increased accessibility for upkeep (no standing water). The substrate provides more surface area for bacterial biofilm growth over an SF wetland, so increased treatment effectiveness may require smaller land areas. For BOD removal, this advantage may not exist (Kadlec, 2002, personal communication). Saving land area is important at many installations and translates into reduced capital cost for projects requiring a land purchase. SSF wetlands are also better suited for cold weather climates since they are more insulated by the earth. Finally, many industrial waste streams, such as landfill leachate, can be treated in reed-bed systems with minimal ecological risk since an exposure pathway to hazardous substances does not exist for wildlife and most organisms.

There are two basic types of SSF wetlands: horizontal flow (HF) and vertical flow (VF). HF systems are more prevalent and thereby have a considerably larger knowledge base, although VF systems are more common in mining applications. Both allow water to flow through permeable, root-laced media, but some vertical flow systems combine an organic substrate with the

permeable media. Large populations of bacteria and beneficial fungi live in the beds as biofilm attached to the media surfaces. VF systems have removal mechanisms similar to those of HF systems but completely different hydraulics.

3.3 Riparian Buffers

While technically not a constructed wetland system, establishment or enhancements to riparian buffers can be used to treat nonpoint sources of pollution. Surface water bodies can be impacted from nonpoint sources of pollution derived from runoff from roadways, agricultural fields, and urban areas. In addition to dissolved chemicals such as road salts, agrochemicals, animal wastes, and oils from leaking vehicles, particulate matter and sediments can be carried into the water body as well. Similarly, in many geological settings, surface water bodies are hydraulically connected to the local groundwater system or aquifer. Therefore, groundwater impacts can eventually find their way into the surface water body as well. Riparian buffers can be established along the boundaries to protect these waters. These buffers are vegetated strips or transitions designed so that dissolved constituents can infiltrate into the rhizosphere and suspended solids can settle out prior to reaching the water body. Also known as corridors, these systems utilize various phytotechnology mechanisms to cleanse and/or contain runoff.

These systems are typically situated parallel to the banks of the water body to be protected along the entire length. In the case of rivers or streams, these systems can be very long. The design of riparian buffers is based on the hydraulic load coming into the vegetated area. For suspended matter, sufficient residence time must be provided for settling and sedimentation to occur. Creating small berms or swales along the length of the system can facilitate this reduction. These parallel rows allow some ponding and infiltration to occur so that the nonpoint source pollution is captured and then introduced into the highly bioactive rhizosphere of the vegetation. Once in the rhizosphere, phytosequestration, rhizodegradation, phytoextraction, phytodegradation, phytovolatilization, and evapotranspiration can lead to the containment or remediation of the constituents. Figure 3-3 shows a cross-sectional view of a riparian buffer.

Similarly to wetland treatment systems, riparian buffers can use all classes of vegetation on the wetland indicator status. Wetland indicator status refers to categories that the U.S. Fish and Wildlife Service (USFWS) has given to most plants in the United States. USFWS has compiled data on the habitat characteristics of plants and categorized species by their frequency of occurrence in a wetland habitat.

These categories are as follows:

- Obligate wetland plants (OBL) occur almost exclusively in wetlands (>99% of the time).
- Facultative wetland plants (FACW) usually occur in wetlands (67–99%).
- Facultative plants (FAC) are equally likely to occur in wetlands or nonwetlands (34–66%).
- Facultative upland plants (FACU) usually occur in nonwetlands (67–99%).
- Upland plants (UPL) occur almost exclusively in uplands (>99%).

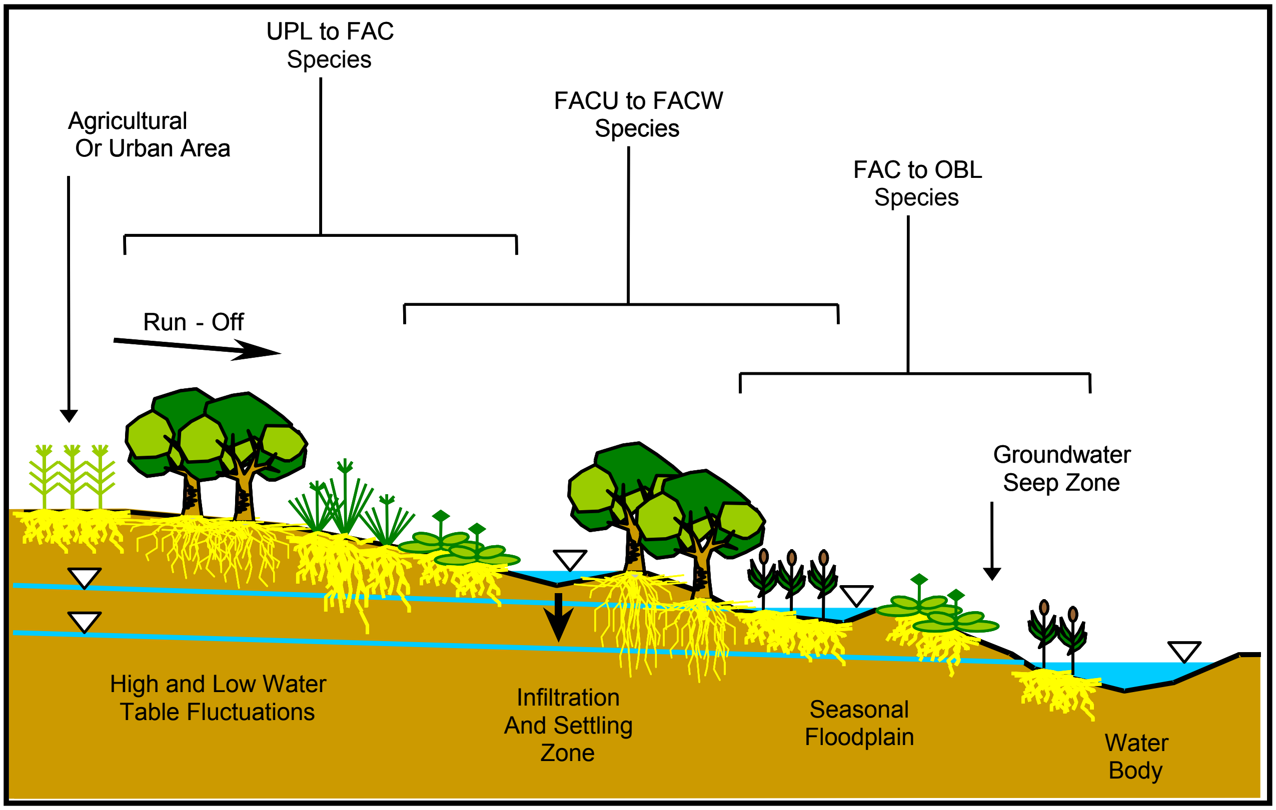

Figure 3-3. Cross-Sectional Schematic of a Riparian Buffer System

Closest to the water body, which can typically be within the flood plain, OBL and FACW species can be used. Moving upland, vegetation in the transition between saturated and unsaturated soils can include FACW, FAC, and FACU species. Finally, in the upland areas closest to the nonpoint source pollution, FACU and UPL species can be planted. Table 3-1 provides lists of common phytotechnology species based on their wetland indicator status.

Table 3-1. Common Species Used in Phytotechnology Applications Based on the Wetland Indicator Status

Wetland species (OBL, FACW)	*Betula nigra* (river birch) *Carex* sp. (sedges) *Myriophyllum aquaticum* (parrot feather) *Phalaris arundinaceae* (reed canarygrass) *Phragmites* sp. (reeds) *Scirpus* sp. (bulrushes) *Spartina* sp. (cordgrasses) *Taxodium distichum* (bald cypress) *Typha sp*. (cattails)
Facultative species (FACW, FAC, FACU)	*Andropogon* sp. (bluestem grasses) *Celtis occidentalis* (hackberry) *Elaeagnus augustifolia* (Russian olive) *Eucalyptus camaldulensis* (river red gum) *Festuca rubra* (red fescue) *Lolium* sp. (ryegrasses) *Lotus corniculatus* (birdsfoot trefoil) *Morus rubra* (mulberry) *Populus* sp. (poplars) *Populus deltoides* (cottonwoods) *Salix* sp. (willows) *Trifolium hybridum* (alsike clover) *Trifolium repens* (white clover)
Upland species (FACU, UPL)	*Agropyron* sp. (wheatgrasses) *Bouteloua* sp. (grama grasses) *Coronilla varia* (crownvetch) *Festuca arundinacea* (tall fescue) *Helianthus annuus* (common sunflower) *Panicum virgatum* (switchgrass) *Pinus taeda* (loblolly pines) *Solidago rigida* (stiff goldenrod) *Trifolium pratense* (red clover)

Note: Some of the species listed above may be considered noxious or invasive. It is advised that state regulations or agricultural extension services be consulted prior to plant selection.

4.0 APPLICATIONS

Applications for constructed wetlands are varied and include treatment of stormwater runoff; municipal, industrial, and agricultural wastewaters; and landfill leachate. Recently, treatment wetlands have been used at hazardous waste sites to treat contaminated groundwater emanating from either seeps or pump-and-treat systems. The U.S. Department of Defense (DOD) has used wetlands to treat aircraft and runway deicing chemicals, ordnance or pink water, and wash rack effluent.

Table 4-1 lists the applications discussed in this guidance document and the typical contaminants of concern for each application. Information on treatment efficiency for a specific contaminant may be obtained from a variety of applications. For example, nitrate is generally not a major constituent of concern for mine drainage, but some mine water contains high levels due to explosive residuals. Data on nitrate removal can be obtained from wetlands built to treat municipal or agricultural wastewaters.

Table 4-1. Typical Contaminants Found in Various Wastewaters

Application	Major constituents[3]	Other[4]
Stormwater	BOD, oil and grease, TSS, TN, TP,	Trace metals
Municipal	BOD, COD, TSS, VSS, T-Nitrogen, NH_4, NO_3, T-Phosphorus, ortho P, Fecal coliform	Trace metals
Mine Drainage	Acidity, iron, sulfate	Trace metals
Industrial Wastewater		CBOD, TSS, VSS, TDS, COD, Coliform-Fecal, TN, N, NO_3, TKN, NH_4, TP, metals, oil & grease, pH, chlorine, sulfate/sulfides, phenols, cyanide petroleum hydrocarbons
Remedial Wastewater		CBOD, TSS, VSS, TDS, COD, Coliform-Fecal, TN, N, NO_3, TKN, NH_4, TP, metals, oil & grease, pH, chlorine, sulfate/sulfides, phenols, cyanide petroleum hydrocarbons
Landfill Effluent	BOD, COD, TSS, TN, NH_4, TKN, TP, TN, NO_3	Synthetic & petroleum hydrocarbons, heavy metals, VOCs, SVOCs, PAHs
Agricultural Wastewaters	BOD, COD, TSS, TN, NH_4, TKN, TP, TN, NO_3 , Fecal Coliform	Pesticides, herbicides
On-site Wastewater	BOD, COD,TSS, VSS, T-Nitrogen, NH_4, NO_3, T-Phosphorus, ortho P, Fecal coliform,	

Kadlec, Robert H., Knight, R.L., *Treatment Wetlands*, CRC Press, Lewis Publishers
[2] http://firehole.humboldt.edu/wetland/twdb.html
[3] Constituents commonly found in all wastewater for this application.
[4] Constituents vary depending on the specific site.

Figure 4-1 indicates the relative percentage of treatment wetlands organized by type in a population of 650 constructed wetland sites. The data is an estimate for North America only. (Kadlec and Knight, 1998)

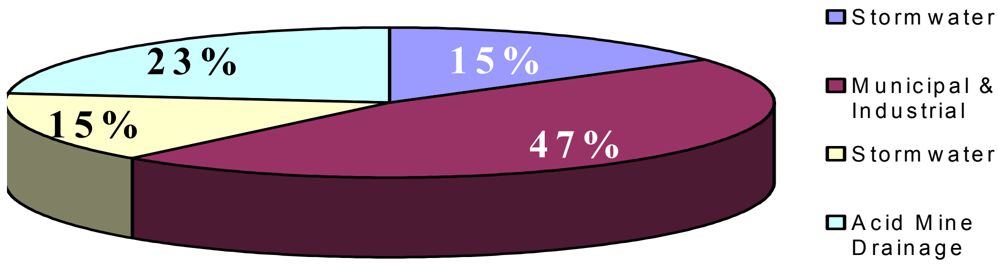

Figure 4-1. Percentage of Constructed Wetland Uses

During the development of this guidance document, a survey was distributed to the ITRC mailing list to collect case studies to evaluate successful demonstration and full-scale applications. Figure 4-2 presents the percentage of constructed wetland applications out of the 24 case studies collected with this questionnaire. The case studies are included in Appendix A. The following sections describe in greater detail the specific constructed wetland applications considered by the team in the development of this guidance document.

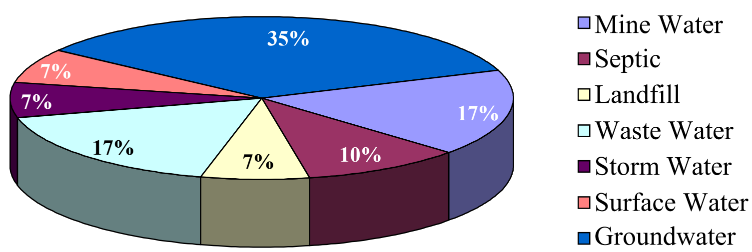

Figure 4-2. Distribution of Wetlands According to Application

4.1 Stormwater Runoff (Nonpoint Source)

Constructed wetlands are designed to treat stormwater runoff by retention, settling, and biological uptake of contaminants. Constructed wetlands are also designed to reduce peak discharges of infrequent large storm events to reduce occurrence of downstream flooding. Stormwater runoff from urban, industrial, and agricultural areas usually contains low levels of contaminants. Table 4-2 gives concentration data for typical nonpoint source (NPS) runoff.

Typical sources of contamination in stormwater runoff include

- oil, grease, and gasoline from vehicles leaking onto roadways and parking areas;
- pesticides, herbicides, and fertilizers from agricultural and urban areas;
- sediment from construction operations; and
- metals from vehicle exhaust, rust, paint, tires, and engine parts.

Table 4-2. Typical Stormwater Pollutant Concentrations from Nonpoint Sources

Constituent	Urban Runoff (mg/L)	Industrial Runoff (mg/L)	Residential Runoff (mg/L)	Highway Runoff (mg/L)	Agricultural Runoff (mg/L)
BOD	20	9.6	3.6 – 20	--	3.8
Oil & Grease	2.6	--	--	30	--
TSS	150	94	18 – 140	220	55.3
TN	2.0	1.8	1.1 – 2.8	up to 3.4	2.3
TP	0.36	0.31	0.05 – 0.40	up to 0.7	0.34
Cadmium	0.0015	--	--	--	--
Chromium	0.034	--	--	--	--
Lead	0.140	0.20	0.07 – 0.21	0.55	--
Nickel	0.022	--	--	--	--
Zinc	0.20	0.12	0.046 - 0.170	0.38	--

Note: -- indicates data not available.
(Source: Data reported as seen in Kadlec and Knight, 1996; Horner and Skupien, 1994)

Constructed wetlands are an excellent buffer between pollutant sources and receiving waters. Typically surface flow wetlands are employed for this application. Riparian buffers are used to treat nonpoint sources of pollution. As described before, the vegetated strips or transitions in a riparian buffer are situated parallel to the banks of water bodies and are designed so that dissolved constituents can infiltrate into the rhizosphere and suspended solids can settle out. Table 4-3 shows typical average removal efficiencies and some of the variability in performance of selected surface flow stormwater wetlands.

Table 4-3. Surface Flow Wetland Treatment of Stormwater at Selected Sites

Percent Removal by Wetland						
Constituent	**McCarrons, MN**	**Hidden Lake, FL**	**Hidden River, FL**	**Dust Marsh, CA**	**Wayzata, MN**	**Orange County, FL**
TSS	87	83	86	77	96	89
N (type)	24 (TN)	62 (NH_3)	79 (NH_3)	15 (NH_3)	- 44 (NH_3)	61 (NH_3)
TP	36	7	70	56	77	40
Lead	68	54	83	88	96	83

(Source: Kadlec and Knight, 1998)

4.2 Municipal Waste Treatment

For a number of years, constructed wetlands have been used for treatment of municipal wastewater. These systems have been built to remove suspended solids, BOD, organic compounds, metals, and nutrients (nitrogen and phosphorous) through natural physical, chemical, and biological processes occurring within the wetland. Ninety percent of all types of municipal wastewater treatment wetlands are less than 250 acres, with 82% treating less than one million gallons per day of wastewater. Most of the wetlands used in the last 20 years have been for polishing municipal wastewater (tertiary treatment). Wetlands are now being considered effective as a secondary treatment process as well.

Constructed wetland technology can be used in combination with other secondary treatment technologies. For example, a constructed wetland could be placed upstream from an infiltration system or secondary wetlands could discharge to enhancement (SF) wetlands for polishing. USEPA does not recommend using constructed wetlands for primary treatment of raw municipal wastewater.

Primary treatment constitutes a settling process for removal of settleable solids from wastewaters. Secondary treatment is a continuation of primary treatment by removing certain constituents such as BOD and TSS to levels of 30 mg/L. Lastly, tertiary (advanced) treatment refers to further reduction in the BOD and TSS concentrations as well as removal requirements for nitrogen and phosphorous. Table 4-4 shows the typical characteristics of municipal wastewater treated in constructed wetlands.

Table 4-4. Typical Characteristics of Municipal Wastewater Most Often Treated in Constructed Wetlands

Constituent, mg/L	Septic Tank Effluent	Primary (Settling Pond) Effluent	Oxidation Pond (Lagoon) Effluent
BOD	129–147	40–200	11–35
Soluble BOD	100–118	35–160	7–17
COD	310–344	90–400	60–100
TSS	44–54	55–230	20–80
VSS	32–39	45–180	25–65
TN	41–49	20–85	8–22
NH_3	28–34	15–40	0.6–16
NO_3	0–0.9	0	0.1–0.8
TP	12–14	4–15	3–4
Ortho-Phosphate	10–12	3–10	2–3
Fecal Coliform (log/100 mL)	5.4–6.0	5.0–7.0	0.8–5.6

(Source: USEPA, 2000)

Both SF and SSF constructed wetlands have been used in municipal wastewater treatment to meet a 30 mg/L BOD and 30 mg/L TSS secondary discharge standard. If discharge limits (or waste load allocation) are very low for TSS, BOD, and/or nutrients (nitrogen and phosphorus), then constructed wetlands may not be a cost-effective treatment option compared to other more conventional treatment systems.

SF wetlands can treat pollutant loadings of 6 g/m^2-d BOD and 5 g/m^2-d TSS (based on maximum monthly influent rates) to secondary effluent standards (USEPA, 2000). With sufficient pretreatment and wetland area, SF constructed wetlands can meet discharge standards of less than 10 mg/L BOD, TSS, and total nitrogen (TN) on a monthly average basis. Permanent phosphorus removal in SF wetlands is small and is the result of adsorption to solids and plant detritus.

SSF systems have generally not performed well in consistently reaching advanced treatment goals (< 10 mg/L BOD and TSS) with primary treatment effluent (USEPA, 2000). TSS removal is good at loading rates up to 20 gm/m^2-d based on maximum monthly influent TSS (USEPA, 2000). BOD removal is not as good as TSS, and usually controls the design requirements to meet secondary standards (30 mg/L effluent concentration). BOD removal is good at loading rates less than 6 gm/m^2-d based on maximum monthly influent BOD (USEPA, 2000). Also, ammonia removal through nitrification is inconsistent due to oxygen-limited anaerobic conditions of the SSF wetlands. If ammonia removal is required, a separate process should be used in conjunction with SSF wetlands. SSF wetlands are well suited for microbial removal of nitrate via denitrification, but biodegradable organic carbon may be the limiting factor. Organic nitrogen from primary effluent is easily removed since it is associated with the suspended solids. Phosphorous is partially removed in SSF wetlands, but the effectiveness decreases over time. Phosphorous removal by plant harvesting is limited to only about 0.055 gm/m^2-d, so SSF wetlands should not be expected to meet discharge standards for phosphorous on a long-term basis (USEPA, 2000).

If discharge limits for nitrogen and phosphorous are low, harvesting of vegetation may be required to remove the nitrogen and phosphorus that may be released during plant senescence. SF wetlands can be designed to remove nitrogen by providing sufficient open water areas (for aerobic nitrification of ammonia to nitrate) and fully vegetated areas (for anaerobic denitrification of nitrate to nitrogen gas). SF wetlands with large open water that attract waterfowl will be a source of fecal coliform. The background concentrations of various parameters that can commonly be found in SF wetlands treating municipal wastewater are in Table 4-5.

While pathogens are partially removed in SSF wetlands, disinfection of the effluent is normally required to meet discharge limits. Metals are removed through sulfide precipitation and adsorption. SSF wetlands should not be used to treat pond (lagoon) effluents because algae may cause clogging. SSF wetlands may be used to effectively treat secondary effluents so the system consistently meets secondary standards but are not recommended as a remedy for inadequately operated activated sludge systems due to potential clogging from solids.

SF wetlands treating tertiary wastewaters for polishing can be used for recreational benefits because of the reduced human health risks associated with them. For SF constructed wetlands treating secondary wastewater, wildlife and other ecological populations may be equally abundant but human access may be restricted at least in the inlet areas since pollutants pose increased health risks. SSF wetlands pose little health risks since they are under ground. Odors may be a problem at the inlet piping for wetland treatment systems receiving septic tank and primary effluents where the release of anaerobic odors can occur. Mosquitoes are not a problem for properly constructed and operated SSF wetlands. Mosquito populations can be controlled at SF wetland areas through various O&M controls (keeping dead vegetation cleared, reducing the accumulation of pools of shallow stagnant water with water level operational controls, and using larvicides) and maintenance of a balanced ecosystem (fish, beetles, birds, and bats will prey on mosquitoes and their larvae).

Table 4-5. Typical Background Concentrations of Various Parameters Found in SF Wetlands Treating Municipal Waste

Parameter	Range, mg/L	Typical, mg/L
TSS	2–5	3
BOD, SF - open water	2–8	5
BOD, SF - fully vegetated	5–12	10
TN	1–3	2
NH_4-N	0.2–1.5	1
TP-soil	0.1–0.5	0.3
FC, cfu/100 mL	50–5000	200

If the discharge limits are below these values, then wetlands alone should not be considered as an applicable treatment alternative. Table 4-6 gives typical removal efficiencies of wastewater contaminants.

Table 4-6. Typical Municipal Wastewater Characteristics and Removal Efficiencies

Pollutant	Influent Concentration	Removal Efficiency
BOD	20–100 mg/L	67–80%
Suspended Solids	30 mg/L	67–80%
Ammonia Nitrogen	15 mg/L	62–84%
Total Nitrogen	20 mg/L	69–76%
Total Phosphorus	4 mg/L	48%
Cd Cu Pb Zn	10 ug/L 50 ug/L 50 ug/L 300 ug/L	50–60% 50–60 % 50–60 % 50–60 %

(Source: Kadlec and Knight, 1996)

4.3 Mine Drainage

Mine drainage is typically defined as water that has contacted rock that contains reactive minerals. These minerals are primarily trace metal and iron sulfides, which are unstable in the presence of air and can react to release metals and acid. Although the water that has contacted waste rock, tailings, or mine workings typically causes the most problems, water that is associated with processing of the ore can also be problematic. In particular, water that has contacted the rock placed on leach pads may contain cyanide or excess acidity and could require treatment.

Mine drainage impacts are extremely large. Nationwide, over 19,300 km (12,000 miles) of rivers and streams and over 730 square km (180,000 acres) of lakes and reservoirs are adversely affected by contaminated water draining from abandoned mines (Kleinmann, 2000). Geologists searching for ore deposits were among the first to observe that wetlands can accumulate metals. Concentrations of trace metals in wetlands can exceed 1000 mg/kg, indicating the presence of a metal deposit in the watershed. Copper concentrations in some Canadian wetlands reached 2–6% (Sobolewski, 1997). Natural wetlands receiving mine drainage were also capable of removing significant amounts of metals and appeared to offer an alternative treatment approach (Eger et al., 1980; Weider and Lang, 1982; Eger and Lapakko, 1988). Based on these observations, wetlands began to be constructed in the mid-1980s to treat various types of mine drainage.

Although many of the initial systems were designed on empirical relationships, recent designs are based on a more thorough understanding of chemical processes and on both the successes and failures of the past. The different types of systems used in mining applications have been summarized in recent reports by the Acid Drainage Technology Initiative task forces, and portions of this section and Section 6.4.1 have been taken, with permission, from these reports (Skousen et al., 1998; ADTI, 2003, in preparation).

The quality of the mine drainage is a function of rock chemistry and mineralogy and can contain various concentrations of trace metals, iron, manganese, aluminum, and sulfate. Typical concentration ranges for both coal and sulfide ore mine drainage are shown in Table 4-7.

The primary method used to classify mine drainage for the purpose of designing a wetland treatment system is based on net acidity/net alkalinity and pH. Acid drainage has an excess of acidity (total acidity > total alkalinity) and typically has a pH less than 6. In alkaline drainage, the total alkalinity exceeds the total acidity, and the pH is greater than 6.

Net alkaline drainage can be treated in surface or subsurface wetlands, and although surface wetlands can remove some metals from acid drainage, the only way to effectively increase the alkalinity is through the use of a SSF. In some cases, the construction of an anoxic limestone trench prior to the wetland can be used to sufficiently increase alkalinity (Skousen et al., 1998) (see Appendix A, Case Study #22).

Table 4-7. Typical Characteristics of Mine Drainage Water

	Coal Mine Drainage		Metal Mine Drainage	
	Net Acid	**Net Alkaline**	**Net Acid**	**Net Alkaline**
pH	3–4	6.5–7.5	3–4	6.5–7.5
Acidity	100–10,000	<0	100–10,000	<0
Sulfate	1,000–10,000	100–3,000	1,000–10,000	100–3,000
Iron, total	10–1,000	<10–100	10–1,000	<10
Aluminum	10–1,000	<1	1–100	<1
Manganese	5–100	<30	2–25	<2
Copper	ND–1	ND	1–100	0.1–1
Zinc	ND–5	ND	10–1,000	1–10
Cadmium	ND	ND	0.05–1	0.01–0.1
Lead	ND	ND	0.5–10	0.01–0.1

Notes: Except for pH, all concentrations are in mg/L. The trace metals found in mine drainage are site-specific. The ones listed in this table are fairly common (e.g., Cu and Zn) or are of particular concern due to their toxicity (e.g., Cd and Pb). Although coal-mine drainage can contain trace metals, iron, aluminum, and manganese are the major metals of concern. ND denotes not detected.

Over a thousand wetlands have been built to treat mine drainage and range in size from less than an acre to over a thousand acres. Case Studies #6, #9, #22, #23, and #26 present further information on wetlands used to treat mine drainage. Three of these case studies contain performance data (see Table 4-8). Refer to Appendix A for additional information.

Table 4-8. Reported Removal Efficiencies from Case Studies Collected in 2002

Case Study #	Site Name	Initial Concentration	After Treatment Concentration	System
25	Coal-mine drainage Cagle, TN	Fe 100 mg/L	Fe 2 mg/L	Anoxic limestone drain prior to surface flow wetland
26	Rising Star Mine, Shasta County, CA	Cd 0.072–0.47 mg/L	Cd 0.009–0.303 mg/L	Subsurface, vertical flow; compost substrate overlying limestone gravel
29	Dunka Mine Babbitt, MN	Ni: 1.5–5.5 mg/L	Ni: 0.2–1.5 mg/L	Surface flow wetlands, peat substrate

Typical removal efficiencies for common mine water parameters are summarized in Table 4-9.

Table 4-9. Typical Range of Removal in Wetlands Constructed to Treat Mine Drainage

Parameter	Coal Mine Drainage	Metal Mine Drainage
	Typical removal efficiencies	Typical removal efficiencies
pH	>6	>6
Acidity	75–90%	75–90%
Sulfate	10–30%	10–30%
Iron	80–90+%	80–90+%
Aluminum	90+%	90+%
Copper	NM	80–90+%
Zinc	NM	75–90+%
Cadmium	NM	75–90+%
Lead	NM	80–90+%

Note: NM denotes not measured.

4.4 Industrial Wastewater Treatment

Although industrial wastewater quality varies among industries, constructed wetlands can be used for industrial wastewater treatment. Because of the high concentrations of pollutants in raw industrial wastewater, pretreatment prior to discharge to a treatment wetland may be necessary. Table 4-10 summarizes the typical wastewater composition from various industrial sources that use or might consider using a constructed wetland. Current applications of constructed wetlands include refineries, vehicle-washing operations, compressor stations, leachate treatment, pulp and paper processing, food processing facilities, tanneries, fertilizer industry, paint industry, textile mills, etc.

Wastewater from the paper-and-pulp industry receives primary (settling) and secondary (conversion of organic matter/BOD using an activated sludge process) treatment. Constructed wetland systems are used at the paper-and-pulp mills to provide additional advanced/tertiary treatment to meet effluent standards (Kadlec and Knight, 1996)

Some sources of wastewater generated in refineries include process operations, cooling tower blowdown, tank drainage, and stormwater runoff. Raw wastewater typically receives primary treatment for oil-water separation and clarification. Secondary treatment includes trickling filters, treatment with activated carbon, oxidation ponds, activated sludge processes, and aerated lagoons. Constructed treatment wetlands are used to provide advanced secondary/tertiary treatment at the refineries. The wetlands detailed in Table 4-11 treat wastewaters that originate from petrochemical facilities, but the data can be extrapolated to several sources outside the petroleum industry (i.e., equipment wash racks). The site at Mandan, North Dakota, is an Amoco oil refinery. The wetland pond system receives wastewater from the plant after pretreatment by an oil/water separator and lagoon. The Amoco system, which has been in existence since before 1972, has demonstrated treatment longevity for industrial applications.

Table 4-10. Typical Pollutant Concentrations in a Variety of Industrial Wastewaters

Pollutant	Units	Pulp and Paper	Petroleum Refinery	Paint Production	Textile Mills	Starch Production
BOD_5	mg/L	100–500	10–800	–	75–6,300	1,500–8,000
COD	mg/L	600–1,000	50–600	19,000	220–31,300	1,500–10,000
TSS	mg/L	500–1,200	10-300	–	25–24,500	100–600
VSS	mg/L	100–250		16,000	100–400	–
TDS	mg/L	–	1,500–3,000	–	500–3,000	–
NH4+	mg/L	–	0.05–300	–	–	10–100
TN	mg/L	–		90	10–30	150–600
TP	mg/L	–	1–10	25	–	–
pH		6–8	8.5–9.5	6.9	6–12	3.5–8
Sulfates/ sulfides	mg/L	–	Nondetect–400			
TOC	mg/L	–	10–500			
Oil and Grease	mg/L	–	10–700			
Phenols	mg/L	–	0.5–100			

(Adapted from a table in Kadlec and Knight, 1996)

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Some sources of wastewater generated in refineries include process operations, cooling tower blowdown, tank drainage, and stormwater runoff. Raw wastewater typically receives primary treatment for oil-water separation and clarification. Secondary treatment includes trickling filters, treatment with activated carbon, oxidation ponds, activated sludge processes, and aerated lagoons. Constructed treatment wetlands are used to provide advanced secondary/tertiary treatment at the refineries. The wetlands detailed in Table 4-11 treat wastewaters that originate from petrochemical facilities, but the data can be extrapolated to several sources outside the petroleum industry (i.e., equipment wash racks). The site at Mandan, North Dakota, is an Amoco oil refinery. The wetland pond system receives wastewater from the plant after pretreatment by an oil/water separator and lagoon. The Amoco system, which has been in existence since before 1972, has demonstrated treatment longevity for industrial applications.

Case studies collected during the development of this guidance document included one site treating industrial wastewater contaminants at Savannah River (see Appendix A, Report #21). The site treated copper concentrations of 50 ug/l to less than 10 ug/l using a surface flow wetlands system.

Table 4-11. Typical Removal Efficiencies of Contaminants at Industrial Facilities

Wetland Type and System	Contaminant	Influent (mg/L)	Percent Removal
SF wetland-pond, oily water, Mandan, ND	Oil & Grease	2.10	94
SF wetland-pond, oily water, China	Oil & Grease	0.84	65
SSF, oily water, Houston TX.	Oil & Grease	-------	90
SSF, vehicle wash water, Surprise, AZ	Oil & Grease	-------	54–92
SF wetland-pond, oily water Mandan, ND	TSS	35.0	86
SF, oily water, Richmond, CA	TSS	20.0	45
SF wetland-pond, oily water, China	TSS	181	77
SSF, refinery effluent pilot-scale, Germany	Phenanthrene	0.385	99.9
SF wetland-pond, oily water, Mandan ND	Phenol	0.08	79
SF, floating aquatic plants (water hyacinth)	Phenol	-------	81
SF wetland-pond, oily water, China	Phenol	0.027	63
SF, floating aquatic plants (water hyacinth)	Benzene, Toluene	-------	> 99
SF, floating aquatic plants (water hyacinth)	Naphthalene	-------	86
SF, floating aquatic plants (water hyacinth)	Diethyl Phthalate	-------	75
SSF, microcosm, UNM, Albuquerque, NM	Benzoic acid	40.0	99

Notes: ---indicates data not available. Data compiled from Moshiri, 1993; Kadlec and Knight, 1996; Machate, 1997; and Tchobanoglous and Burton, 1991.

Wastewater from textile mills varies significantly based on the manufacturing process and products. Textile mills use traditional wastewater processes to treat this wastewater. Although no data is available, the mills’ wastewater appears to be compatible with the constructed wetland technology.

Due to the diverse sources and high-pollutant concentration of industrial wastewater, as mentioned before, wastewater undergoes primary and sometimes secondary treatment before being introduced into the wetland for advanced/tertiary treatment. The considerations and decisions involved in choosing a constructed wetland as a treatment option are discussed in Sections 5 and 6.

4.5 Remedial Activities Wastewater Treatment

Constructed wetland treatment technology is being increasingly used to treat hazardous waste sites managed under the federal Comprehensive Environmental Response Compensation and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA) and state programs. The use of constructed wetlands at such sites is usually considered as part of a comprehensive remedial program.

DOD, in particular, has a considerable number of active and closed landfills that generate leachate and require remediation. These sites often have consistent, large-flow volumes with low

concentrations of contaminants that can be treated with constructed wetland projects. Hazardous waste contamination treatable by constructed wetlands includes petroleum hydrocarbons, VOCs, nutrients, BOD, chemical oxygen demand (COD), TSS, PAHs, some semivolatile compounds, and metals. Sufficient data does not exist at this time to demonstrate that wetlands can effectively and safely treat polychlorinated biphenyls and other persistent chlorinated organic compounds. Characteristics of hazardous waste landfill leachate discharging to constructed wetlands in New York and the associated removal efficiency is presented in Table 4-12.

Table 4-12. Typical Landfill Leachate Characteristics and Removal Efficiencies

Pollutant	Influent Concentration (mg/L)	Removal Efficiency
Alkalinity as $CaCO_3$	2,440	79%
Phosphorous	1.9	99%
Ammonia Nitrogen	230	91%
BOD	70	95%
Copper, total	0.030	89%
Iron, total	51	98%
Lead, total	0.013	100%
Nickel, total	0.065	82%
Benzene	0.0055	94%
Xylene	0.045	98%

(Source: Mulamoottil et al., 1999)

Constructed wetlands could provide cost savings where traditional long-term pump-and-treat technology is used to treat groundwater by pumping contaminated groundwater into a wetland. Once again, the low operations and maintenance costs coupled with the extended savings over years or decades may result in significant savings. Some sites may not even need pumping if gravity flow is possible. A subsurface barrier can be used to direct contaminated groundwater into a constructed wetland. Current federal regulation pursuant to RCRA and CERCLA has flexibilities regarding on-site management of contaminated media.

Currently under way is a study of natural attenuation, through degradation, of chlorinated hydrocarbons plume in a natural wetland (USGS, 1997) at the Aberdeen Proving Ground (APG) in Maryland. The Canal Creek area at APG had been used to develop, test, and manufacture military-related chemicals since World War I. Most of the experimental plants were located between two branches of the tidally influenced Canal Creek. Investigations in this area identified a large volume of groundwater contaminated by VOCs including trichloroethylene and 1,1,2,2-tetrachloroethane. From 1995 to 1996, the USGS and other researchers studied the extent of contamination and the likely effects of natural attenuation of these contaminants as this groundwater entered the tidal wetlands associated with Canal Creek. Laboratory microcosm studies indicate that significant degradation of VOCs occurs in anaerobic wetland sediments. Removal processes include sorption and subsequent microbial and abiotic anaerobic degradation to nonhazardous substances, as well as possible aerobic degradation and volatilization. The

researchers concluded that natural attenuation of VOC-contaminated groundwater is feasible using wetlands coupled with groundwater inflows. Other hazardous waste sites are planning to harness the remediation method through design of constructed treatment wetlands.

Another example of a site cleanup using constructed treatment wetlands is Operable Unit 5 at Elmendorf Air Force Base, Alaska. Constructed in 1996, this full-scale constructed SF wetland treats aviation fuel (JP-5) contaminated groundwater from sources located around the base. Pump and gravity flow devices consolidate the wastewater and transport it to the wetland. Results from the Elmendorf Air Force Base cleanup (Case Study #17, Appendix A) indicates that treatment of the groundwater is occurring, though biological activity within the wetland changes as a result of Alaska's colder climate. Case Study #10 from Brighton, Ontario documents a decrease in recognizable denitrification in wastewater, though a dramatic reduction in biological activity is observed during winter months when the temperature is 1–2°C (33–35°F).

Table 4-13 documents the treatment efficiencies of constructed wetlands used to treat contaminated groundwater from an industrial waste landfill as noted in the Fort Edward Case Studies #10 and #24 (Appendix A).

Table 4-13. Reported Concentrations of Groundwater Contaminants from Two Case Studies from Fort Edward, New York

Constituent	Beginning concentration	Following treatment
Fe	20 mg/L	0.3 mg/L
Vinyl Chloride	700 ug/l	5 ug/l
Other VOCs	700 ug/l	65 ug/l

4.6 Effluent from Sanitary or Domestic Landfills

One of the most studied and applied remediation uses of constructed wetlands is for leachate treatment (Mulamoottil et al., 1999). Leachate composition is primarily related to landfill age and the type of waste in-place. Temporal variability is shown in Table 4.14. The concentrations of leachate differ as well from site to site because of variability in landfill design, annual precipitation, evapotranspiration, groundwater flow, and age.

Constructed wetlands may be ideal for treating small, irregular pulses of leachate from a landfill because they can treat a variety of contaminants over a wide range of concentrations. Furthermore, their long lifespan and low maintenance requirements make them ideal for satisfying the long-duration postclosure care requirements.

A case study from Clinton County, New York (Case Study #27) is a six-step impoundment with an influent of subsurface leachate from a former (capped) municipal waste landfill. The project is full scale and is in its sixth year of operation. Values for the primary leachate constituents beginning in July of 1996 are reported in Table 4-15.

Table 4-14. Landfill Leachate Characteristics

Pollutant	< 2 Years Old (mg/L)	> 10 Years Old (mg/L)
pH	5.0–6.5	6.5–7.5
BOD	4,000–30,000	< 100
COD	10,000–60,000	50–500
TOC	1,000–20,000	< 100
Total Solids	8,000–50,000	1,000–3,000
TSS	200–2,000	100–500
Total N	100–1,000	< 100

(Source: NCEL, 1991)

Table 4-15. Leachate Removal Efficiencies for a Constructed Wetland in Clinton County, New York

	July 1996 "Initial Condition"	April 2002	July 2002 (Case Study Report Date) Post-treatment
TDS	1600 mg/L	656	706
Fe	25 mg/L	21 mg/L	0.18 mg/L
VOCs	225 ug/l	6 ug/l	<5 ug/l

4.7 Agricultural Wastewater

Use of constructed wetlands to treat or mitigate the impact of agricultural wastewater is a fairly recent development, and the number of systems that have been installed is still small. The use of constructed wetlands in agriculture will be modified as our understanding of the complex processes is improved and refined as more systems are installed and monitoring data is gathered over a longer period of time.

Recent laws and regulations governing concentrated animal feeding operations (CAFOs) are addressing the conditions under which operators are allowed to discharge effluent from wastewater lagoons under wet conditions. These regulations have led to a renewed interest in constructed wetlands for treating or minimizing impacts to receiving waters from wastewater resulting from hogs, cattle, dairy, or poultry operations. While the data shows that properly designed wetlands can be effective in treating agricultural wastewater, a great deal of research is needed to understand the complex relationships between the science, designs, and operation.

The characteristics of agricultural wastewater vary considerably depending on the animal being managed and the type of operation. The character of agriculture (in particular livestock operations) has changed markedly in the last few decades, where open ranches have given way to confined operations. Corresponding herd sizes have increased to meet demands for animal products. The

handbook published by the Natural Resource Conservation Service (NRCS) (*Animal Waste Management Field Handbook*, 1992) is an excellent source of information to describe the characteristics of animal wastewater. Typical pollutants found in agricultural wetlands are described in Table 4-16.

Agriculture wastewater can be treated using SF wetlands. As discussed in previous sections, SF wetlands provide excellent removal of BOD, TSS, and nutrients. The characteristics of agricultural wastewater vary from one animal type to another; and as part of the predesign evaluation of the project (see Section 5.0), an accurate assessment of the wastewater should be made by a lab analysis for five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), un-ionized ammonia (NH_3), ionized ammonia or ammonium (NH_4-N), nitrate (NO_3-N), and total phosphorous. High salinity has been observed in many swine lagoons in Oklahoma and should be considered as a limiting factor in plant growth.

The concentrations of pollutants in agriculture wastewater are generally high and require some degree of pretreatment. In the animal waste industry, anaerobic digesters, as well as primary and secondary treatment lagoons, are generally used to provide pretreatment. A surface flow wetland should utilize the effluent from the secondary lagoons that are generally of lower concentration. To protect the plant community, the SF wetland should not receive wastewater with an ammonia concentration above 100 mg/L (NRCS, 1991). Researchers, such as Reaves et al. (1995), found that concentrations of 200 to 300 mg/L ammonia in the influent damages the growth of young cattail shoots used to treat swine effluent. However, the same concentration has not been found to damage mature cattails. Reaves et al. (1995) maintain that while NH_3 may be toxic, the nontoxic form (NH_4) was not damaging. Since most of the ammonia is volatilized in the lagoons, it is safe to use the effluent that contains only ammonium.

The use of subsurface flow wetlands to treat agriculture wastewater has been limited due to high concentration of TSS in wastewaters. The TSS has a tendency to plug the connected pores of the soil, causing a reduction in permeability and Darcy velocity.

4.8 On-Site Wastewater

On-site systems are SSF wetlands that treat septic-tank effluent and provide better than secondary levels of treatment. These systems are used for single-family dwellings, public facilities and parks, apartments, and commercial developments and have been used to treat on-site wastewater in Louisiana, Arkansas, Kansas, Kentucky, Indiana, Mississippi, Tennessee, Colorado, Texas, and New Mexico.

Table 4-16.   Common Constituents and Treatment Efficiencies in Agricultural Wastewaters

	BOD mg/L			TSS mg/L			NH_4-N mg/L			TKN mg/L			TP mg/L		
	Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal
Swine (a)										30	8	73	Na	7	73
										50	> 10	< 80	Na	10-20	10-17
Swine (b)	76.6	7.9	89.7	135.7	15.5	88.6	55.6	8.6	84.5	73.7	12.2	83	28.4	6.8	76.1
Dairy (c)	910.3	155.6	83	483.4	113.2	77	199.4	99,8	50	215.3	113.1	47	25.3	10.8	57
	910.3	67.6	93	483.4	30.7	94	199.4	21.6	89	215.3	30.4	86	25.3	4.2	83
Dairy (d)	357	202	43	1596	48	97	12	2.4	80	119	17.5	85	25	3.9	84
Dairy (e)	705	242	66	542	142	74	126	65	48				33	17	48
Cattle (f) W	29.9	9.51	68	128	53	59	5.54	1.80	68				12.66	7.19	43
Cattle (f) C	31.08	5.07	84	111	33	70	8.02	1.55	81				20.83	7.67	63
Poultry (g)			41.84						36.2			38.52			

USEPA 2001 Constructed Wetlands and Wastewater Management for CAFOs, including case studies by:

(a) Humenik et al.
(b) McCaskey & Hannah
(c) Reaves & Dubowy (2-stage system) 1996
(d) Hermans & Pries
(e) Moore & Niswander 1996
(f) Cooper & Testa 1995 C = Cool Season, W = Warm Season
(g) Hill & Rogers

They typically occupy only a few hundred square feet in area. In general, good performance has been demonstrated for removal of BOD, TSS and fecal coliform, with variable performance for removal of ammonia nitrogen. On-site wetlands have similar advantages to SSF wetlands used to treat municipal wastewater in that they are cost-effective and have low maintenance requirements. However, they differ from the larger SSFs in that the treated effluent typically discharges to subsurface soils instead of surface water.

The constructed wetland is made up of a shallow (18" deep) pit lined with 30 mil plastic, usually filled with clean gravel or small rock, and planted with evenly spaced wetland plants. The effluent from the septic tank flows slowly through a network of perforated pipe into the filter material where the wetland plants aid in the treatment. Most of the treatment is accomplished below ground level where TSS is removed by filtration and BOD is reduced through anaerobic degradation. Some of the treatment takes place in the root system of the plants where pathogens and nutrients from the household wastewater are degraded and removed. The volume of water is reduced by the uptake of water by the plants in the bed. At least one hundred feet of subsurface absorption field is required in the event that treated wastewater is discharged from the wetland. This is much less than the lengths of lateral lines required for conventional drain field systems.

In some designs, the effluent from an upstream SSF wetland discharges to a second SSF wetland that can be unlined to allow treated wastewater to infiltrate to soil for subsurface disposal. Treatment train variations include use of subsurface absorption fields, evapotranspiration (ET) trenches, and direct surface discharge or land application with or without subsequent disinfection and aeration.

Although there are several design approaches, on-site wetland systems are usually designed for an effluent with less than 10 mg/L BOD, less than 10 mg/l TSS, and 10 mg/L total nitrogen. These wetlands will usually have a hydraulic retention time (HRT) in the wetland bed of greater than 6 days. A three-bedroom home with six persons and an assumed BOD loading of 100 g/cap-d (grams per capita per day) would require a SSF wetland of 100 m^2 in area. This is based on a removal rate for BOD of 6 g/m2-d to achieve an effluent quality of less than 30 mg/L (USEPA, 2000). However, design criteria may vary from place to place. As reported by USEPA (2000), the SSF area for a three-bedroom home varies from less than 10 m^2 to greater than 100 m^2, the HRT varies from 1.3 to 6.5 days, the aspect ratio varies from 71:1 to 1.8:1, and gravel size varies from 0.65 cm (0.25 in) to 7.5 cm (3.0 in).

A variation of the on-site wetlands is the manufactured modular system, often referred to as "packaged treatment system." These are self-contained, integrated systems designed to treat small flows. They use physical techniques (sedimentation, filtration), chemical processes (adsorption), and biological mechanisms (bioaccumulation, nitrification, and denitrification) to treat the water. The system consists of a series of sedimentation chambers and constructed wetlands within a modular tank.

5.0 EVALUATION, DESIGN, AND CONSTRUCTION OF CONSTRUCTED WETLANDS

5.1 Evaluation

Design of a constructed wetland is an iterative process involving site-specific data. Prior to design and construction, site conditions must be evaluated to assess the efficacy of the proposed constructed wetlands.

Preliminary data required to begin the design process includes
- water budget and influent characterization;
- treatment objectives (discharge standards to be met); and
- site suitability (site topography, available area, hydrogeology, and climatic patterns).

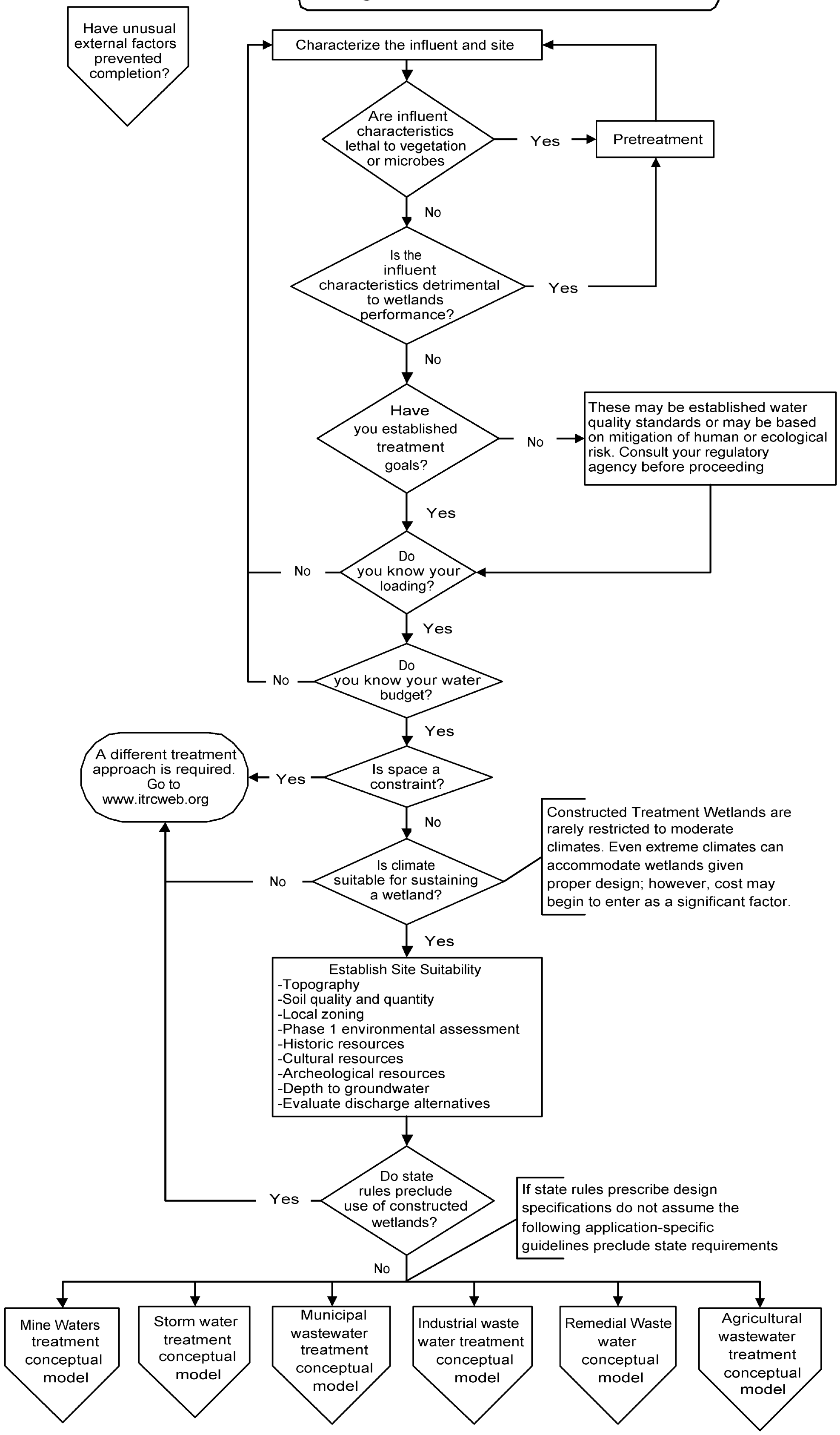
The following sections present a thorough discussion of the manner in which that data is obtained and how it is evaluated. Figure 5-1 is a decision tree that summarizes the information that is presented in the following sections and should be used to evaluate whether a constructed wetland is an appropriate treatment system to meet the treatment goals for any specific site. Keeping regulators involved and in concurrence throughout development of the conceptual design will help the project proceed smoothly.

5.1.1 Water Budget

A detailed water budget must be completed to design a successful constructed wetland. The water budget is a quantification of all water flowing into and out of wetland cell(s). Flows into the wetland can include natural flows, process flows, stormwater runoff, precipitation, ice thaws, and groundwater. Natural flows would include inflows from upland sources such as ponds or lakes. Water leaves the wetland via evaporation, transpiration, the wetland outlet system, and possibly groundwater. The difference between all inflows and outflows is storage.

Water budgets are not simple to calculate because of the transient nature of most inflows and outflows and the lack of site-specific data. This is especially true for stormwater wetlands. Instead, estimates are made and appropriate safety factors are applied based on the confidence of the data. Nevertheless, the water budget is a critical aspect of design. If an improper design causes water to leave the wetland at a greater rate than all the combined inputs for an extended period of time, then the wetland will dry out and overall treatment effectiveness could be compromised. If the opposite occurs, greater inflow than outflow, then the wetland will flood and/or retention times may not be sufficient for adequate removal of contaminants. Thus, all movements of water in the wetland must be accounted for in the water budget.

Figure 5-1. Site Characterization



Groundwater flows into or out of the wetland cell must also be considered (unless an impermeable liner is used to prevent impact to groundwater). Conversely, groundwater contributions or releases can be a significant portion of the water budget. Some treatment wetlands are designed to maximize groundwater discharge for regulatory or water resource reasons.

Besides water leaving the wetland outlet structure, evaporation and transpiration are the most significant contributors to outflow. Together these terms include all losses above the air/water interface and are commonly termed evapotranspiration (ET). ET estimation techniques in use include pan evaporation and various energy balance quantification methods. ET is seasonally variable.

The water budget is a simple mass balance/accounting of all inflows and outflows and can be summarized as:

$$P + SWI + GWI = ET + SWO + GWO + S$$

Where

P	=	Precipitation
SWI	=	Surface water inflow
GWI	=	Groundwater inflow
ET	=	Evapotranspiration
SWO	=	Surface water outflow
GWO	=	Groundwater outflow
S	=	Change in storage

The quantity of influent water per unit time must be known to size the wetland. Flow data collection and flow estimates should take into consideration the amount, duration, and timing of the influent processes or events.

Treatment of stormwater or runoff requires quantification of unsteady and intermittent flow. Flow rates vary dramatically over time because of normal variability in precipitation patterns. Ideally, historical stormwater flow rate data at the proposed wetland location will be available for determining the design storm, a basis for wetland sizing. Design storm can be also determined by direct flow measurements collected over a year or at least the wet season. Historical climatological data and information about the contributing watershed(s) can be used for determining flow rates. Certain rules of thumb include sizing a stormwater wetland based on 1–5% of the contributing watershed.

Flow measurement is possible if a channel, weir, stormwater outfall, or other possible location exists where source flow quantity can be measured either directly by a flow device or indirectly by recording water levels. The flow instrument should be capable of measuring low rates because some long duration storms produce runoff with low flow rates that contribute significantly to wetland inflows.

5.1.2 Influent Characterization

Influent characterization is the process of determining the quantity and quality of the water to be treated. Influent quantity will be a volumetric flow rate versus time analysis. Sometimes this is straightforward, such as with a process waste stream with consistent flow rates and known compositions. However, quantity calculations can be difficult for unsteady or intermittent flows. Water quality is a measure of the influent constituents and their respective concentrations. Accurate water quality determination is critical in creating a properly functioning wetland.

Common questions to be asked during the influent characterization process include the following:

- What is the flow?
- What are the average/expected maximum/minimum flows?
- How might these change in the future?
- What are the parameters of concern?
- What are the concentrations for the parameters of concern?
- Is the water net alkaline or net acid?

Once the water is well-characterized, performance limits and the required length of time for treatment must be established. Influent water quality must be determined to understand whether a constructed wetland can effectively treat the influent. Water quality analysis reveals the contaminants and their concentrations. Although the contaminants of concern may be known ahead of time, additional samples should be analyzed to confirm their concentrations and characteristics. Samples should be taken at the point where they are expected to be introduced to the wetland.

A useful measurement for comparing various constructed wetland alternatives is the contaminant-loading rate. The treatability of a contaminant affects design retention times and, consequently, a wetland's size. It should also be emphasized that the contaminant concentrations typically vary over time and that low, average, and peak flow must be determined over a representative time interval. Once contaminants are identified, their respective concentrations determined, and flow regimes estimated, contaminant-loading estimates can be determined.

In addition to known site-specific contaminants, water quality characteristics that should be assayed include, but are not limited to

- BOD, COD, TOC, TSS, TDS, and coliform
- pesticides, herbicides (USEPA Methods 608, 615, 622,)
- oils and grease, or Total Recoverable Petroleum Hydrocarbons (USEPA Method 413.1 or 418.1)
- priority pollutant VOCs (USEPA Methods 8010, 8015, 8020, and 8240)
- semivolatile priority pollutants (USEPA Method 8270 – extractable organics)
- metals (USEPA Methods 6000 and 7000 series)
- nutrients (total P, TKN, Nitrate/Nitrite, and ammonia nitrogen)
- sulfate, sulfide, and sulfite (USEPA Methods 300.0 and 376.2)
- general parameters of temperature, pH, oxygen, turbidity, and salinity

5.1.3 Treatment Objectives

Constructed wetlands are limited by the ability of the biota to withstand exposure to the environment. In treatment systems, these factors most notably include influent contaminant concentrations and gross water quality parameters such as pH. Contaminant concentrations within the wetland must be below threshold concentrations for biota survival. The concentrations in the discharge after treatment should reach concentrations that will assure compliance with regulatory levels. High contaminant concentrations with low permissible effluent concentrations would require long retention times, hence large wetland areas where flows are appreciable.

Often wetland performance is judged by removal efficiency, which is the effluent contaminant concentration divided by the influent concentration. It should be noted that this value can sometimes be a misleading figure. High removal efficiencies may indicate a high influent concentration with a much reduced effluent concentration; but low removal efficiencies do not necessarily indicate diminished performance, and this should be taken into account when considering such data as presented in the following sections.

Wetlands can also add contaminants to water flowing through them; background concentrations of nitrogen, phosphorous, BOD, and other water quality parameters are not zero. Thus, removal efficiencies are sometimes negative for some chemicals. This must be considered in cases where effluent limits are very stringent, although regulators may be willing to negotiate some permit limits in the case of wetland treatment.

Since wetland treatment is to a large degree a biological process, the time required for treatment may not be acceptable when compared to other technologies such as chemical precipitation. Removal efficiency is typically a function of treatment time, or the retention time of the wetland, water flows may hence require unacceptably large areas to treat to the required cleanup objective.

5.1.4 Determination of Site Suitability

Wetlands are ideally suited to sites having a relatively large available area, a source of year-round water, an appreciable growing season, and a relatively large volume of water requiring treatment with low to moderate contaminant concentrations. Of course, situations like these are seldom the case, and the various factors must be evaluated separately and together. This analysis is usually accomplished during a feasibility study.

Like any treatment technology, site-specific issues need to be addressed before selection of constructed wetlands as a remediation choice. These considerations include the following:

- **Available land area**—Depending on flow volumes, contaminant concentrations, and treatment goals, a treatment wetland may require a considerable area. A small wetland may have difficulty handling large flows from storm events in areas of high rainfall.
- **Topography**—The site should be relatively flat.
- **Soils**—Sandy or permeable soils may require the installation of a liner to contain water in the wetland and prevent infiltration of wastewater to groundwater.

- **Groundwater**—Wastewater infiltration to groundwater may pose regulatory problems, and high groundwater may make construction difficult.
- **Climate**—Treatment effectiveness is generally lower in colder weather, and systems built in cold climates may require substantially greater areas or special operation to meet treatment goals. Hot climates may require supplemental sources of water to prevent drying out.
- **Contaminant concentrations**—Like other biological systems, high concentrations of certain contaminants, even temporarily, can disable a treatment wetland for extended periods. Background concentrations in a wetland may exceed effluent standards in some cases. For example, waterfowl may introduce coliform bacteria that may exceed effluent permit requirements.
- **Biological conditions and ecofactors**—The presence of endangered or threatened species may restrict construction activities. There may be possible risk exposure pathways created by a wetland if located near human or ecological receptors.

Since there are many considerations in treatment wetland implementation, it is advisable to conduct a feasibility study and alternative analysis for treatment technology selection. This involves the site-specific collection and analysis of selected information to evaluate the use of constructed wetlands as the preferred treatment of choice as compared to other treatment technologies.

Topography

Topography is an important factor in selecting a site and wetland type. Elevation differences at the site can affect drainage patterns and erosion potential. Access to the site can be hindered by the presence of valleys, hills, and rock formations. Construction costs are directly affected by the contouring of the site. Wetlands are relatively flat, and the earthmoving needed to create the gentle slopes is costly on sloping sites (Hammer, 1992).

Soils and Geology

Site soils information is necessary to predict hydrology, prepare for excavation, and determine suitability for wetland plants. Soil samples should be collected from several locations in and around the proposed wetland site, including some from beneath the wetland. A professional familiar with the region should analyze the soil and determine its characteristics at various depths. Hydric soils are valuable for starting a new wetland because they have already conformed to wetland (reduced) conditions and they are likely to have seeds and rhizomes of wetland plants. Muck harvesting from an existing wetland is generally limited to projects where a wetland impact has already been permitted and is necessary for some other reason. Relocation of hydric soils from a natural wetland to a constructed wetland may not be advisable since it could contain a seed bank containing exotic or undesirable species. In many situations, constructed wetlands established on upland soils can achieve adequate soil-reducing conditions within a few months of project startup.

Soils should be evaluated for the following:
- USDA soil classification

- percent sand, silt, clay, organic content
- permeability
- field capacity
- cation exchange capacity
- pre-existing concentrations of potential contaminants, including nutrients, metals, pesticides, and trace organics

Wetland bottom and transition area soils directly influence water exchange with groundwater. For example, a continuous clay layer may preclude the need for a liner if one is required to protect groundwater. If flow into the wetland will be intermittent, then low-permeability soils may be desired to maintain saturated conditions. For those circumstances where leakage from the wetland to the groundwater is not desirable, the cell bottoms should have at least 1.5 feet of low-permeability soil. Some highly permeable soils may preclude the use of a wetland or require a liner so that adequate retention times are achieved and untreated contaminants do not result in groundwater impacts. On the other hand, highly permeable soils may be advantageous where groundwater recharge is desirable or where on-site media will be used for an SSF wetland.

The geologic conditions at the site will be another design consideration. It is necessary to evaluate the depth to the bedrock at the site since shallow bedrock could potentially cause problems with construction. A qualified geologist should conduct geotechnical investigations during the preliminary design to characterize relevant subsurface site conditions. Type and composition of underlying rock formations should be identified so that constructability is known. Subsoil characteristics should be assessed for compaction, slope stability, and use as a suitable backfill over buried pipelines. Other geologic conditions that might be important in wetland design are the presence of sinkholes, subsurface channels, crevices, old mine shafts, tunnels, airshafts, and boreholes (Hammer, 1992). All these conditions could cause wetland damage and cost increases to the project and should be investigated prior to construction.

Wetland plants, like most other plants, establish and thrive most readily in loamy soils, which are mixtures of sand, silt, and organic matter. The presence of organic matter in the soil is desirable. Binding sites on the organic soil particles may allow cation exchange, which removes metals from water in exchange for hydrogen and serves as food source for bacteria, especially during the start-up phase. Thus, the ideal wetland condition would be a layer of loamy soil (1 foot to 3 feet) for plant rooting and optimum microbial growth. The loamy soil can overlay a layer of impermeable (higher clay and silt content) soil when leakage is not desirable.

Groundwater and Hydrology

The presence of high groundwater may affect water balance by decreasing the infiltration rate or by acting as a wetland water source. In areas under tidal influence, groundwater contributions can be a significant source of water to the wetland. Clay or synthetic liners may be necessary to control groundwater movement, especially in the case where hazardous materials are present in the wastewater.

Soil-permeability data for the site should be collected and analyzed to determine groundwater effects. Analyzing water levels versus estimated bottom elevations will indicate whether water

will migrate from the cell to groundwater or groundwater will infiltrate into the wetland cell. Groundwater levels should be measured through the four seasons to account for seasonal changes in flow. This investigation should include depth, quality, and whether the groundwater is perched or part of the regional flow system (Hammer, 1992).

Groundwater models can be used for complicated flow patterns. Flows through the proposed bed material can be estimated using Darcy's Law, soil permeability, and water-level measurements. The potential flow or "specific discharge" (V) is:

$$V = Q/A = K\,[(H+d)/d]$$

Where

Q/A	=	Seepage volumetric rate Q per unit area A
K	=	Soil permeability
H	=	Depth of water in the wetland
d	=	Thickness of the liner bed

By definition, the specific discharge (V) is equal to Q/A (cm^3/cm^2/day), which is reduced to cm/day. However, since water only moves through the connected pores, the "seepage velocity" is obtained by dividing the specific discharge (V) by porosity (n). [(V/n) cm/day].

Climate

Several climatic factors affect the design of a constructed wetland. Daily and seasonal precipitation patterns determine the amount and timing of runoff events to stormwater treatment wetlands. Daily and seasonal air temperatures affect biological and chemical processes. Humidity affects temperature and precipitation—both of which are controlling factors in biological and physical processes (Hammer, 1992). Climactic data for a particular region is often available, but information regarding microclimates at and around the site may be sparse. Site-specific data is the most desirable for a successful design.

Climatic factors that are important in treatment wetland design include typical and extreme patterns of sunlight, rainfall, temperature, evapotranspiration, and freezing. The amount of sunlight impinging on the wetland is important since this energy input is the primary driving force for most physical and biological processes. Plant productivity is affected by the amount of sunlight, both directly through photosynthesis and indirectly through the effect of sunlight on air and water temperature. Evapotranspiration from wetlands is highly correlated with the amount of incident sunlight. Microbial processes affecting nitrogen concentrations (e.g., mineralization, nitrification, and denitrification) are all significantly reduced at lower temperatures (Kadlec and Knight, 1996).

While organic-matter decomposition is also slowed at low temperatures, the global affect of cold climates on BOD treatment in wetlands is negligible, owing to a decrease in internal BOD production during colder weather (Maehlum, 1999). Some research indicates microorganisms will adapt to their climate or will be replaced by different species that are tolerable and more

receptive to the new conditions (Machate, 1997). Therefore, the "new" microorganisms replace the "old" and metabolize (remove) contaminants as part of their normal biological activity.

Winter operation presents difficulties not only because of the physical problems with ice buildup and flow problems, but also because the rate of chemical and biological reactions decreases as the temperature decreases (see Case Study #8, Appendix A). However, design techniques exist for the continuing operation of most constructed wetlands during cold winters and freezing conditions. Successful winter operation in surface flow wetlands has been observed in northern winter climates, where snow and the air gap formed under ice can act as insulation. This low-conductivity air gap does not exist in a subsurface flow system, but the combined layers of litter and dry gravel provide sufficient insulation, which can be further augmented with straw or other mulch materials (Kadlec and Knight, 1996).

Biology

Considering existing and postconstruction biology can enhance wetland design. The presence of indicator plants, animals, amphibians, and insects at the project site are good indicators of the existing condition of the soil and depth to groundwater. For example, bladderwort and pitcher plants indicate reduced nitrogen, and many chironomids (a benthic macroinvertebrate) indicate low dissolved oxygen (Hammer, 1992). Wetland plants indicate hydric soils and what could be the remains of a wetland. Just as existing plants will indicate what the current soil and water conditions are, they may also provide useful information on the type of wetland plant species best suited for that site. A qualified environmental scientist should be on the design team to select appropriate wetland plant species and to provide guidance on ecological risk issues.

5.2 Design and Construction

Once it has been determined that a constructed wetland is appropriate for the waste stream and the site, the process continues with the design and construction of the wetland system. While the design of the constructed wetland must follow standard engineering practices and wetlands science, there is no simple "cookbook" method. The actual construction of the wetlands system must consider the unique features of the aquatic and semiaquatic environment that are being developed.

This section discusses the basic design and construction activities that must be considered as part of the process to build a constructed wetland. A decision tree has been developed for each of the major applications considered in this document, including the following:

- Figure 5-2. Stormwater Treatment Decision Tree
- Figure 5-3. Municipal Wastewater Treatment
- Figure 5-4. Mine Waters Decision Tree
- Figure 5-5. Industrial Wastewater Treatment
- Figure 5-6. Remedial Wastewater Treatment Decision Tree
- Figure 5-7. Agricultural Wastewater Treatment Decision Tree

Figure 5-2. Stormwater Treatment Decision Tree

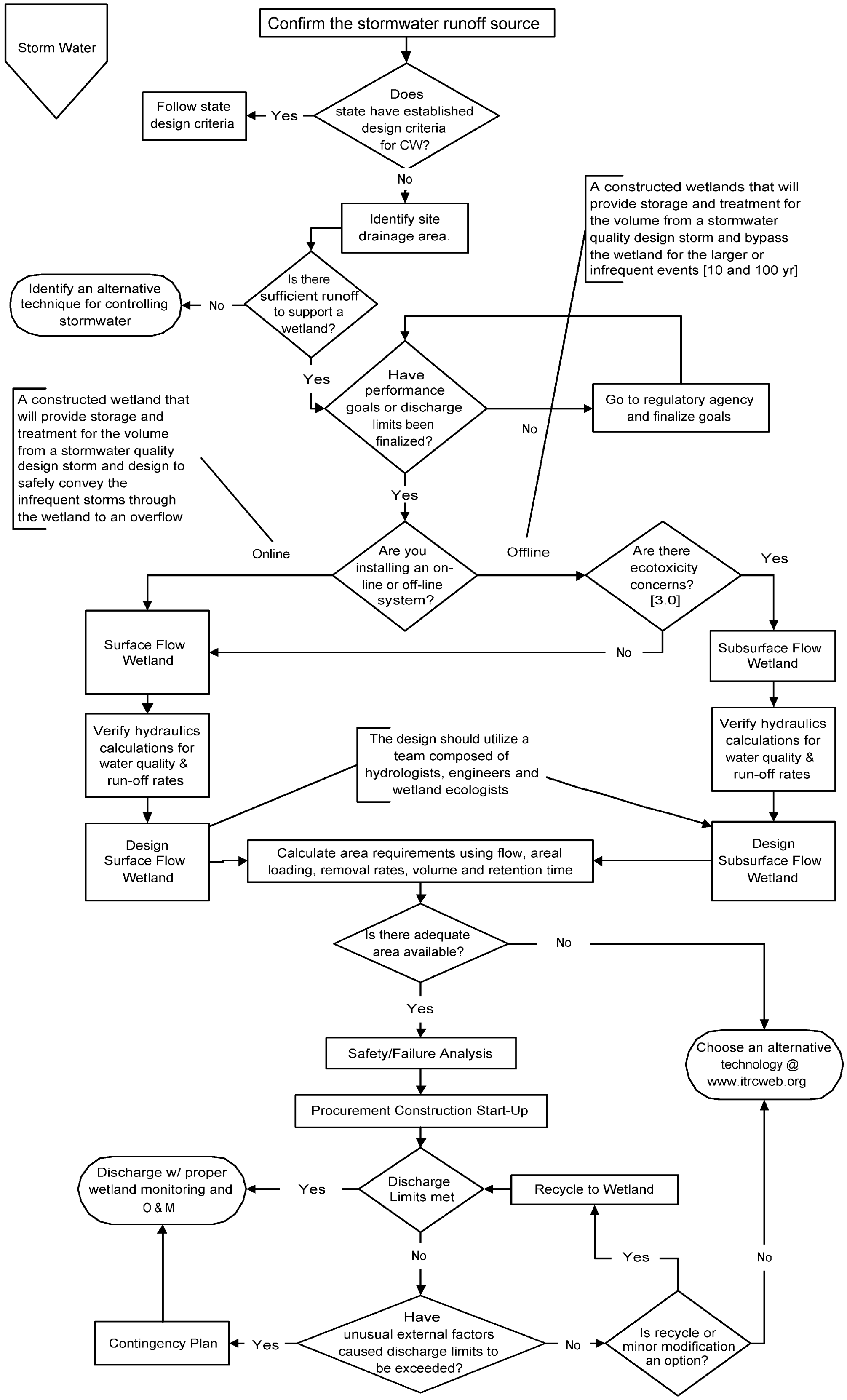


Figure 5-3. Municipal Wastewater Treatment (upgrade or replacement)

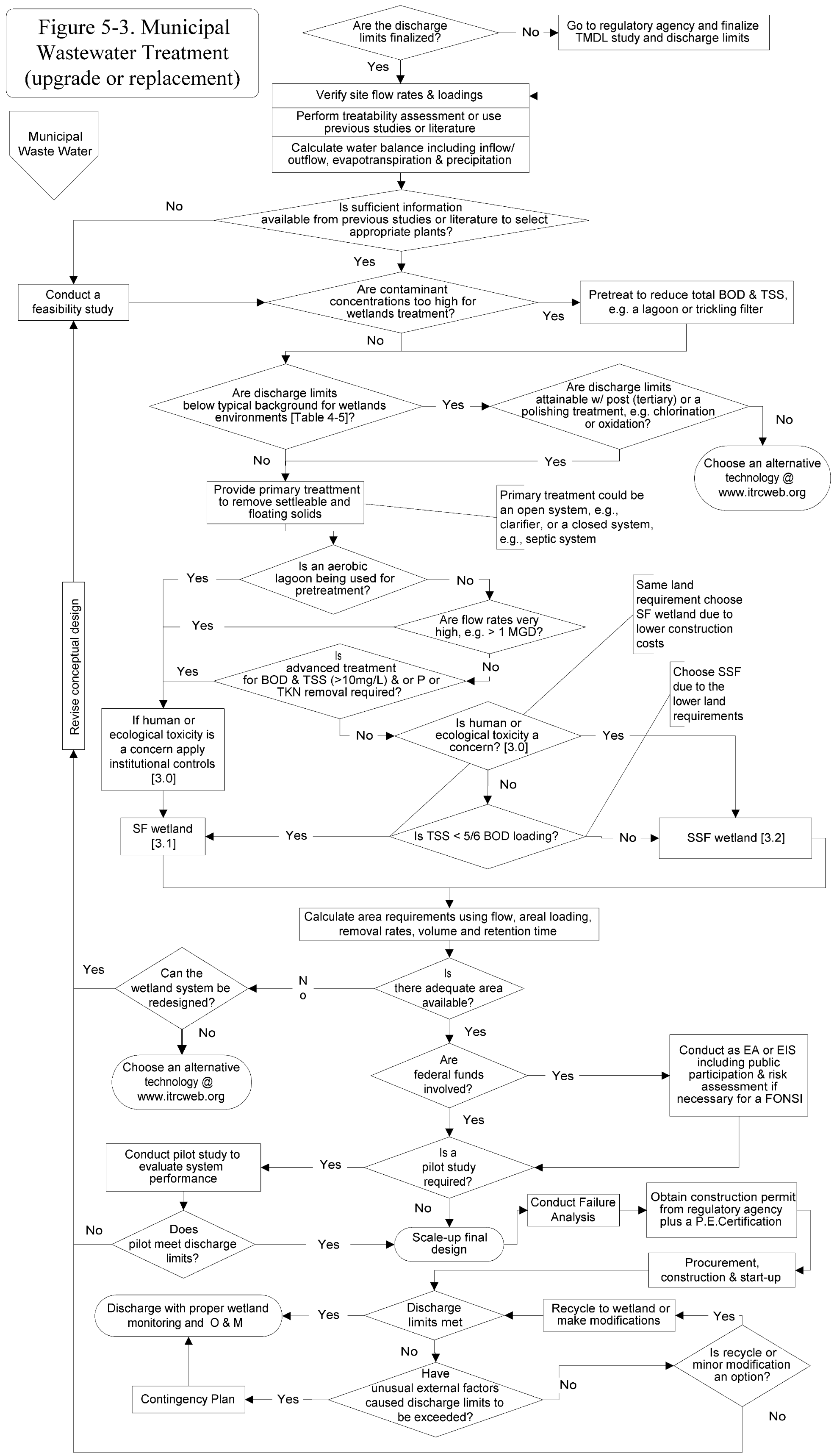


Figure 5-4. Mine Waters Decision Tree

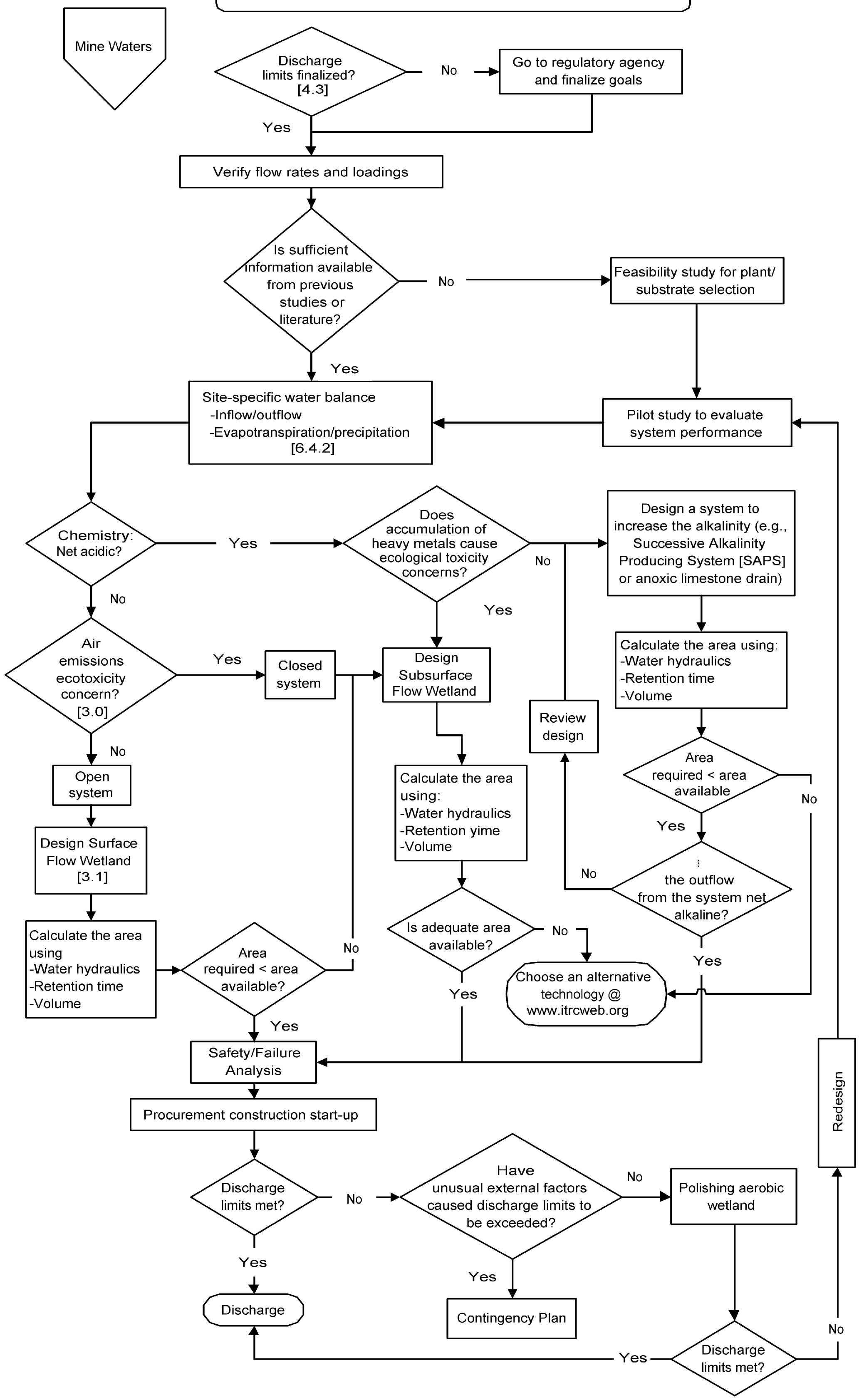


Figure 5-5. Industrial Wastewater Treatment

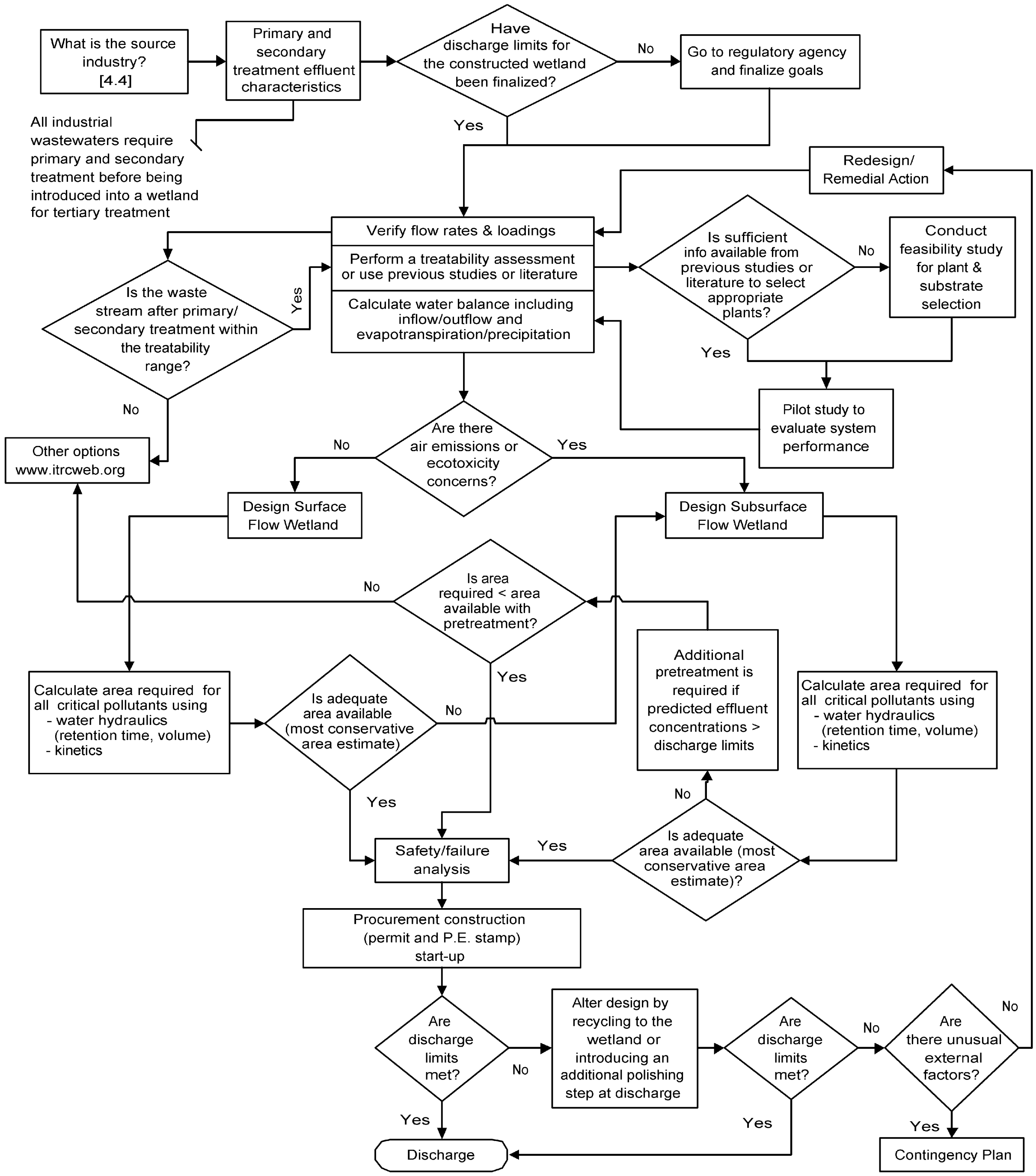


Figure 5-6. Remedial Wastewater Treatment Decision Tree

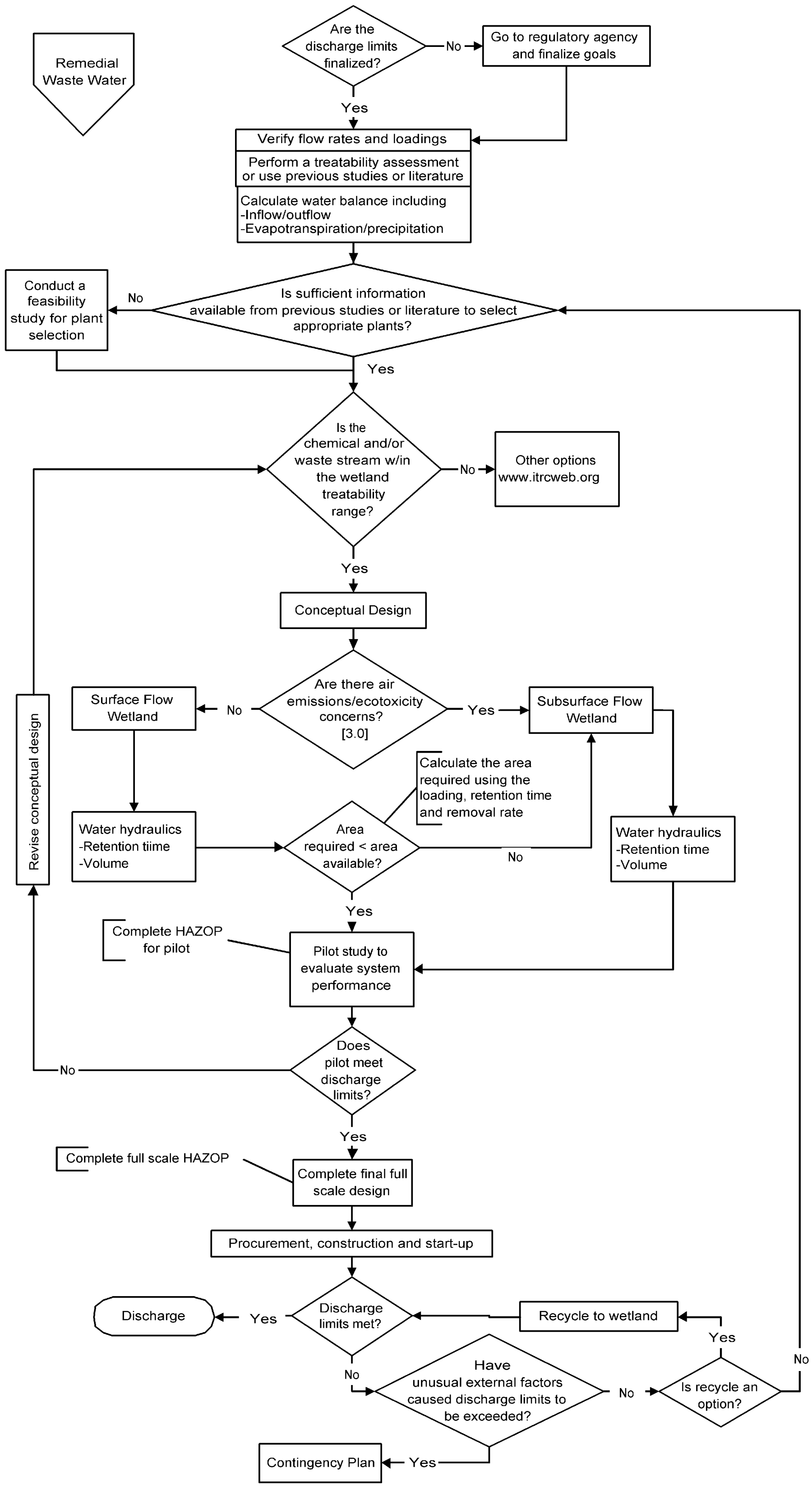
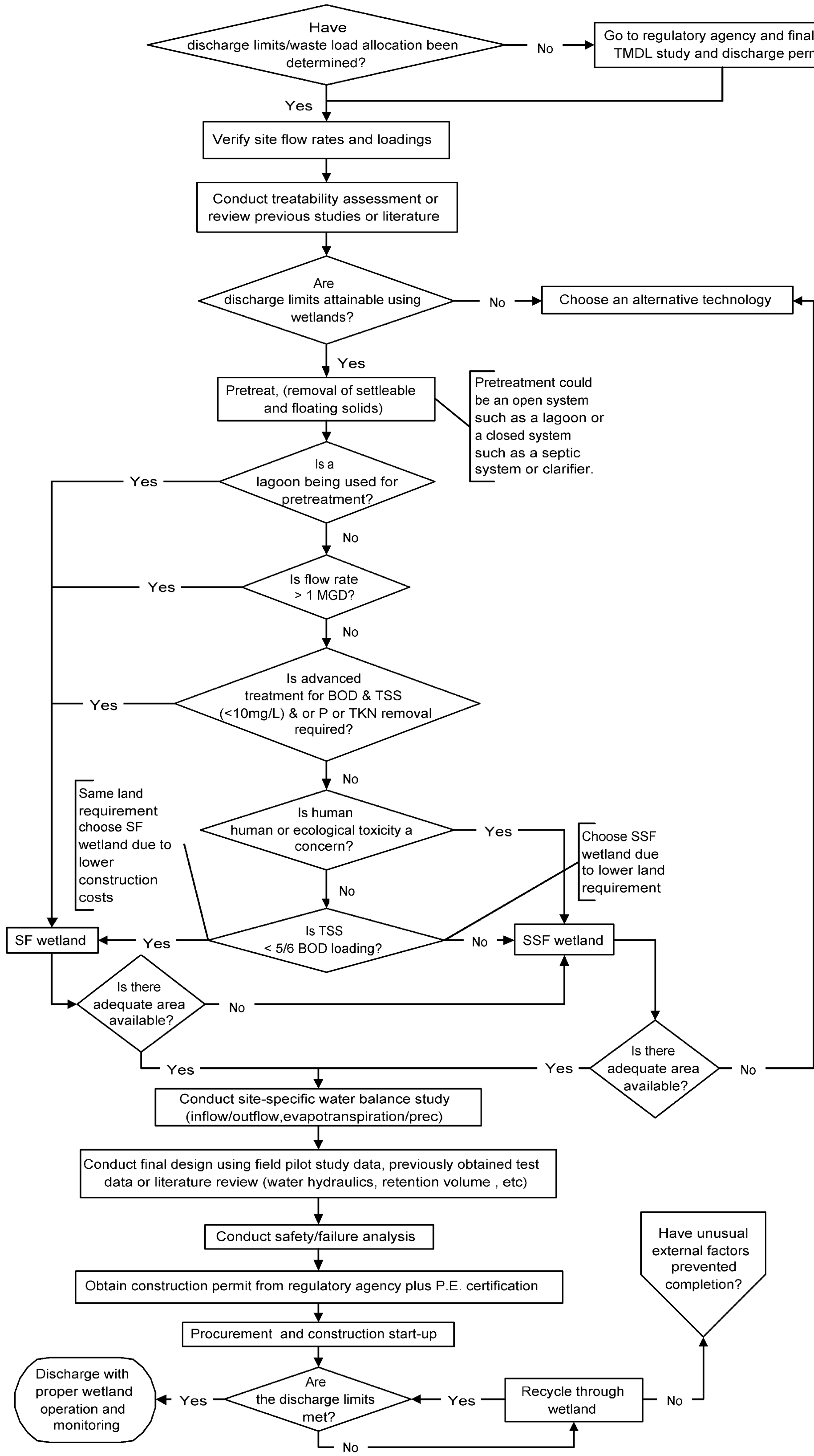


Figure 5-7. Agricultural Wastewater Treatment Decision Tree



A design checklist, in conjunction with the aforementioned decision trees, can be effectively used to plan, review, and study the constructed wetland system performance. This checklist will highlight the data requirements, site needs, and action plans to the site owners, system operators, regulators, and stakeholders. The checklist should include the following:

- ✓ roles and responsibilities of the wetland team
- ✓ treatment goals/project expectations of the site owner, regulators, and the public
- ✓ identification and understanding of stakeholder/public concerns with wetlands as a treatment technology
- ✓ baseline site characterization
- ✓ review of site characterization data
- ✓ treatability assessment (If not enough historical scientific data is available, then pilot/bench-scale testing is necessary.)
- ✓ feasibility studies for plant selection
- ✓ site visits
- ✓ understanding how a wetland can achieve remedial goals
- ✓ proposed design of the wetland system based on type and loading of wastewater
- ✓ work plan for implementing final design
- ✓ a detailed HAZOP study to eliminate safety hazards
- ✓ evaluation of hazards to public health or the environment.
- ✓ monitoring plan for the wetland project
- ✓ operations and maintenance plan and schedule for the wetlands project
- ✓ plan to deal with secondary waste (contaminated plants and/or sediments) that may be generated in the wetland
- ✓ contingency plan if the wetland does not achieve remedial goals
- ✓ site security

5.2.1 Predesign

Prior to actual design, there is additional technical data that is required. While the determination of the suitability of a site for the use of a constructed wetland is made using some site-specific information, predesign information must be a further refinement of that data. The ability to develop a successful design, and by extension a successful constructed wetland, is based on having as complete an understanding of the exact characteristics of the site and the waste stream as possible. Site-specific water budget, an important step of wetland design, has been discussed in the evaluation phase (Section 5.1) and is not described in detail here.

Hydraulics

Residence Time and Loading Rates

The residence time is an estimate of the average time wastewater requires to flow completely through the wetland. In order to get effective treatment, the residence time must be greater or equal to the reaction time needed to achieve the desired effluent concentration.

The residence time is a function of the "reactive" volume of the wetland divided by the flow rate. For surface flow wetlands, the reactive volume is the volume of water above the substrate; while for subsurface systems, it is the volume of water below the substrate. The actual residence time may be less than the calculated value, due to preferential flow. Most designs include a safety factor, which increases the size of the wetland, to account for the potential of preferential flow and the estimates included in the calculation of the reaction rate. The required residence time is a function of the degradation/removal rates and treatment goals and will vary depending on the specific contaminants. Residence times for SF and SSF constructed wetlands are suggested from four to 15 days (Tchobanoglous and Burton, 1991), depending upon contaminant types, their degradation/removal rates, and treatment goals.

Hydraulic loading rate (q) refers to the flow rate per unit area. HLRs typically vary from 0.7–5 cm/d for constructed surface flow wetlands and 2–20 cm/d for constructed subsurface flow wetlands (WPCF, 1990) USEPA's North American Database (NADB), a compendium of actual treatment wetlands in the United States and Canada, lists median values of 1.4 cm/d and 17.4 cm/d, respectively.

Residence time is defined as:

$$T = V/Q \qquad \text{(Equation 5.1)}$$

Where T = residence time (days)
V = wetland volume (cm^3)
Q = average flow rate (cm^3/day)

Hydraulic loading rate is defined as:

$$q = Q / A \qquad \text{(Equation 5.2)}$$

Where Q = avg. flow rate (cm^3/day)
A = wetland area (cm^2)

Another parameter used in sizing wetlands is the areal loading rate (ALR). The ALR is the maximum removal rate of a pollutant mass per unit surface area of a wetland per daily input.

$$ALR = Q \times C / A \qquad \text{(Equation 5.3)}$$

Where Q = influent flow rate (cm^3/d)
C = pollutant concentration (mg/L = g/m^3)
A = surface area (cm^2) of the SSF wetland.

Areal loading rates can be used to give sizing estimates for both planning and final design of wetlands systems from projected pollutant mass loads and effluent requirements.

Depth and Flow

Water flow rate and flow depth are critical aspects for treatment. Flow velocity should be low (less than 0.5 feet/second) and laminar to provide sufficient residence time to achieve the target removal rates of contaminants. Flow through vegetated submerged beds should be at a constant depth throughout the rooted areas. Typical flow depths for SF systems are 0.3 to 2.0 ft. (Tchobanoglous and Burton, 1991), while subsurface systems have flow depths varying from 1.6 to 2.6 ft. (Cooper ,1998).

The design of the constructed wetland system must establish depth of flow throughout the wetland for hydraulic control. In SF systems, the use of spaced, deep open-water sections across the width of the treatment cell can reduce flow channelization, resulting in better overall treatment efficiency. The bottom should be graded flat across the width to avoid creating preferential flow channels.

Flow in horizontal subsurface flow wetlands should be entirely through the rooted soil and sediments, with no continuous free surface water. SSF wetlands with free surface water will result in short-circuiting and inefficient treatment since water flow will follow the path of least resistance, moving quickly across the surface of the wetland and resulting in incomplete treatment. Vertical systems are constructed so that water moves uniformly, either down or up, through the substrate. Water is generally ponded on the surface to help maintain anaerobic conditions and to provide the appropriate hydraulic head.

Internal Flow Paths

Water flows through a wetland in irregular, internal flow paths. In SF wetlands, there are spatially varying areas of open water, dense vegetation, porous substrate (soil and litter layers), and variable flow depths from designed or self-generated microtopographies, high marsh areas, and construction imperfections. In SSF systems, water travels through heterogeneous media with variable hydraulic conductivity, variably porous organic matter, and media penetrated by a complex and changing root and rhizome network.

Internal flow patterns can promote mixing and better treatment, or they can also promote “short-circuiting” and reduced removal efficiency. Short-circuiting is the undesirable rapid movement of water along a preferential path or paths from inlet to outlet. Mixing is desirable for treatment. Factors promoting mixing include wind action, swirls, eddies, dispersion, and diffusion.

For SF wetlands, multiple cells per train are recommended to minimize short-circuiting, and several trains per system are suggested. The recommended aspect ratio (AR) (length/width) should be within 3:1 to 5:1 range for each cell to minimize short-circuiting (USEPA, 2000).

Kinetics

The critical design factor in sizing a treatment wetland is the rate of removal for the contaminant(s) of concern. Removal rates can be defined by kinetic expressions with a specific

rate constant, an areal rate of removal, or a removal per unit volume. Removal rates can also be empirically derived from pilot tests.

Kinetic Expressions

In general, rates of reactions are functions of the concentration of reactants and a specific rate constant, which is a function of temperature. For example, a simple model for the breakdown of BOD in wetland systems, assumes a first-order reaction:

$$-\frac{d\,BOD}{dt} = k\,(BOD) \qquad \text{(Equation 5.4)}$$

Solving the above equation, $BOD_{outlet} = BOD_{inlet} \exp^{(-kT)}$ (Equation 5.5)

where BOD = concentration of BOD (g/L)
k = rate constant (day^{-1})
T = residence time (day)

The rate at which BOD is removed is a function of the BOD concentration in the water. With this type of rate expression, removal rates are high initially when the concentration is high but decrease as the water moves through the wetlands and the concentration decreases.

The first-order model was used by Reed et al. (1995) and Kadlec and Knight (1996). These models can be solved to get a preliminary estimate of the area required for your system.

Reed et al. (1995):

$[Pollutant]_{outlet} = [Pollutant]_{inlet} \exp(-kvT)$ (Equation 5.6)

where kv = volumetric rate constant (day^{-1})
[Pollutant] = concentration of pollutant (g/L)
T =V/Q (equation 5.1)

Kadlec and Knight (1996) incorporated background concentrations of BOD (which could be naturally occurring) with the following model:

$([Pollutant]_{outlet} - P^*) = ([Pollutant]_{inlet} - P^*) \exp(-k_A/q)$ (Equation 5.7)

where q = Q/A (equation 5.2)
P* =background pollutant concentration

Rearranging the terms in the Equations 5.5 and 5.6, the wetland surface area and volume can be estimated. For example, Equation 5.6 now becomes:

$A = -Q/k_A\,[\ln(([Pollutant]_{outlet} - P^*)/([Pollutant]_{inlet} - P^*))]$ (Equation 5.8)

Although Kadlec and Knight (1996) directly introduce the concept of an irreducible background concentration, other models (like Reed et al.) include background concentration as a boundary condition (implied lower limit on effluent concentration) of the model.

Areal Removal Rates

Removal is expressed as mass removed per unit area of wetland, i.e. gm/m^2, and is generally based on empirical observations. Areal removal rates have been used as a rule of thumb in the sizing of municipal wastewater and mine drainage systems.

Volumetric Removal Rates

This approach generally assumes a constant rate of reaction throughout the volume of the wetland (zero-order kinetics). The reaction rate may vary with temperature but does not change with concentration. Again, this method simplifies the system but has been used as a rule of thumb to size subsurface wetlands for mine drainage treatment.

Empirical Measurements

Depending on the type and complexity of the water to be treated, the best approach may be to conduct a feasibility study, especially where water is a complex mixture of constituents, where removal may occur through a variety of processes, or for constituents where little literature data is available. Once the removal has been measured in a pilot test, the rates can be used to estimate the size of the required wetland.

5.2.2 Mechanical Design

Liners

Liners and berms provide the basic containment structure for the constructed wetlands and ensure that the basic hydrologic foundation of the wetlands is met. The structural and watertight integrity of the liner and surrounding berm is essential. Failure of either will result in loss of water, potential water pollution, and potential loss of plants as the water level declines.

Most of the difficulties encountered in the installation of liners in constructed wetlands occur because of the requirement to place soil and/or gravel on top of the liner without destroying the integrity of the liner. When considering a choice of liner, this problem should be considered carefully and preferably discussed with the contractor.

Synthetic liners or clay are used to protect groundwater and maintain the hydrologic regime and to insure that the wastewater receives the required treatment before discharge into the groundwater, streams, or land application site. Materials that are generally used include, but are not limited to, the following: polyvinyl chloride (PVC), polyethylene (high density HDPE and linear low density LLDPE), polypropylene (PPE), and compacted clay.

Many of the first municipal constructed wetlands systems were installed without plastic liners. Concerns over groundwater pollution have imposed very expensive soil-testing requirements on projects that do have soils suitable for compaction. Consequently, the costs associated with testing and soil compaction have driven the cost of using in situ soil up to the level of cost for PVC.

Some of these materials can include a scrim, which is a woven net of nylon or polypropylene embedded in the plastic material or enclosed in the clay. Scrims provide extra strength and resistance to tears in the material. Liners with scrims will cost more.

The installation and testing of liners is an important element of a successful wetland project. Designers should become familiar with the installation process, the range of liner materials, and the different set of specifications associated with each material. For large liner jobs (over 100,000 sf), PVC is the easiest and PE is the most difficult to install. Specifications should include some reference requiring written approval of the subgrade by the liner installer before its installation. Written acceptance of subgrade preparation by experienced liner installers is usually a condition for maintaining manufacturers' warranties.

PVC Liners

Each material has a unique set of properties that are worth consideration. For a given thickness, PVC is generally the least expensive material and the easiest to work with in the field. Minimum thickness for PVC materials to be used in constructed wetlands should be 30 mil or thicker. PVC has the best puncture resistance of all the materials (except those with scrims) and good friction properties. It is also available in large prefabricated pieces. It has the most flexibility but also has the least resistance to ultraviolet degradation. Generally, PVC must be covered to protect it from degradation; however, there are new formulations that are more UV-resistant. Since the wetland construction process generally covers the liner with soil or gravel, PVC is a good first choice.

Polyethylene

Polyethylene comes in two forms for liners: linear low-density polyethylene (LLDPE) and high-density PE (HDPE). HDPE is harder to work with in the field than LLDPE, especially in cool weather. Both are more difficult to work with than PVC. Minimum thickness should be 40 mil (equivalent to 30 mil PVC for puncture resistance). UV resistance is good for both PE materials. Field repairs are easy. Seaming with tape should provide good waterproof characteristics and is easily performed in the field, though welds are usually required to effect a more permanent seal at the seams. The absence of chlorine in the manufacturing process makes this material more environmentally friendly than PVC. Puncture resistance is not as good as PVC, and care must be exercised when placing the liner on soils with rocks, roots, or caliche. It is usually 10% more expensive than PVC.

Polypropylene

PPE use as a liner is recent. As prices have dropped, its installation properties have encouraged the use of this material. Field seaming and field repairs are easy. It has good friction qualities. It

has the best puncture resistance of all three plastics. PPE is available in large fabricated pieces, and it has excellent UV-resistance properties. It is manufactured without chlorine and is probably the most environmentally friendly of the three materials. Its major disadvantage is that it is the most expensive of the three materials.

Clay Liners

Finally, there are clay liners composed of a layer of clay between two scrims of finely woven PPE or polyethylene. This liner material was developed for use in landfills where its chemical-resistance properties are of primary importance. Costs in the West are similar to PPE. Shipping will add significantly to costs as distance increases from the Western sources of material. Its puncture resistance is generally low, and subgrade preparation is extremely important. This material is worth consideration in industrial applications or where landfill leachate is being treated by wetlands.

An alternative to plastic liners is the use of bentonite. Depending on soil characteristics, an amount of bentonite specified as pounds per acre is mixed with the existing soil, wetted, and compacted to make a liner whose characteristics will meet the percolation rate established by the regulatory agency. Costs depend on the in situ soil and the distance from the bentonite supply.

Liners with Scrims

If the project can afford them, liners with scrims such as 60 mil Hypalon, 60 mil XR5, or 45 mil PPE are clearly the toughest and most resistant to puncture, tears, and UV radiation. Vehicles such as front-end loaders and trucks can drive on them, which presents certain advantages in placing the gravel media (subsurface flow wetlands) or soil (surface flow wetlands). The contractor's savings in placing the gravel media or soil may offset the difference in cost of liner materials.

Hypalon has long been an industry standard. Hypalon is a proprietary product manufactured from chloro-sulfonated polyethylene with a nylon scrim. It has excellent UV properties, excellent puncture resistance, good strength, and is available in large prefabricated sheets. It is more expensive, and repair is difficult after aging. The loss of binder in the material makes repairs very difficult and expensive.

XR-5 is a proprietary product. It is a PVC material with a scrim and has very high strength, excellent puncture resistance, is available in large prefabricated sheets, and is easy to repair. XR-5 is the most expensive of all the liners and requires specialized equipment for installation. It is subject to some UV degradation and is made with chlorine.

Reinforced 45 mil PPE has all of the advantages of PPE but with higher strength. It is UV resistant, has excellent puncture resistance, is easy to field install and repair, and is manufactured in large sheets. It is not a proprietary product and is produced by at least three different manufacturers so pricing is competitive. It is an expensive product compared with 30 mil PVC.

Berms

Berms should be of sufficient height to retain the wetlands flow, account for storm events, and provide appropriate freeboard to allow for sedimentation. Up-slope berms are also designed to divert surface runoff. Down-slope berms are designed to retain the gravel bed and/or maintain the level of the wetlands. Berm compaction should be 90% of the maximum Proctor. Berm slope can range form 2:1 to as much as 20:1 depending on the design specifications and wetland requirements. Slopes of 5:1 or less should be considered if muskrats are likely to be present. Biologists have discovered that the shallower slopes are not attractive to muskrat tunneling (staff biologist, Bosque del Apache NWR, New Mexico).

Occasionally, berms are constructed to prevent flood damage to the wetlands. Berms then become flood control levies and should be designed accordingly with riprap protection, vehicle access for inspection (10 foot width on top), and erosion-control planting for berm stabilization. Minimum width on top should be 24 inches for foot traffic.

Inlet and Outlet Structures

Constructed wetlands require structures that can uniformly distribute wastewater into the wetlands, control the depth of water in the wetlands, and collect the treated effluent leaving the wetlands. In designing these structures, ease of construction, ease of maintenance, and operator safety and visibility should be the primary considerations for the designer.

<u>Flow Distribution Structures</u>

For gravity-flow situations, simple “V” notch or horizontal weirs will work very well. These structures should be covered with lockable lids that are easy for the operator to open and inspect. Construction is concrete block on a concrete slab. The use of precast units should also be considered. Often, precast units for underground construction will cost less than site-built units.

For small systems, there are several manufacturers of flow splitters that use reinforced PVC for the housing and PVC piping drilled with holes. These types of units work well with small flows (10,000 gpd or less). Because the PVC enclosure is fragile, it must be protected from accidental contact with mowers or other equipment.

<u>Flow Distribution Piping</u>

Once the influent has left the flow distribution structure, wastewater must be uniformly distributed in the front end of the wetlands. For subsurface flow wetlands, distribution piping can take the form of perforated piping placed in the bottom of the wetlands; or in warmer climates where freezing is not a problem, a series of adjustable tees placed on top of the gravel will serve to equally distribute wastewater. In subsurface flow wetlands, other alternatives for the distribution piping are large leachfield distribution chambers such as 12-inch to 24-inch-diameter perforated PE drainage piping or large diameter, half-pipe sections. Care must be exercised to prevent precipitates from forming and clogging the holes. For surface flow wetlands, similar techniques will also work. Distribution can be improved by the installation of additional tees.

Flow Collection Piping and Level-Adjust Structures

Flow collection is the reverse of flow distribution, and similar piping can be installed in reverse. In the 1988 USEPA manual on constructed wetlands, it was suggested that hydraulic performance could be improved by placing wetlands on a slope. In theory, this is a good idea; however, in practice, there are several problems. The first problem is that the idea is based on uniform flow through the wetlands (surface or subsurface both have hydraulic resistance). During low-flow periods, the front end of the wetlands will have little or no water. Once the plants have been established, this would not be a problem, but during start-up this is a significant issue. This leads to the second problem of establishing the plants. If the bottom is sloped, then all the water drains to the low end, and there is insufficient water for plant growth. For example, a 100-foot long wetland with a 1% slope will have water standing 24 inches at one end and 12 inches at the front end. In practice, it is much easier to set the hydraulic gradient by using adjustable pipes on swivels, removable pipes of different lengths, or adjustable stoplogs that allow the level to be adjusted to match the flow. The pipes can be adjusted to match the changing hydraulic resistance as the wetland matures.

When wetlands are placed on sloping ground, multiple cells are sometimes constructed to reduce the excavation and earthwork costs. Level-control structures can be combined with cascades to add aeration capabilities.

Debris Screens and Other Structural Components

Surface flow wetlands will typically drop a large quantity of leaves. During storm events, entire plants can be uprooted and float down stream to the collection piping or outfall structures. Unlike algae or duckweed, this larger debris will cause the collection piping to plug. Therefore, debris screens should be placed in front of these structures.

Treatment Media: Gravel, Sand and Soil

Although no hard rules can be given, the general principle is to select treatment media materials that are within a few sieve sizes. For example, specify gravel between ½ inch to 1 inch, or pea gravel from the #8 to 3/8 inch sieve. This will produce the material with the greatest void ratios, and testing will routinely show void ratios greater than 40%. Examining the gravel pit's standard sieving operations can be used to develop other combinations.

Gravel specification should have a maximum permissible percentage passing the #100 or #200 sieve. One or two percent is ideal, and washed, river run gravel can often meet these specifications. This specification can be relaxed if this 1% or 2% standard is difficult to meet. Excessive amounts of fines will settle out in the haul from the pit; and when dumped into the wetlands, these fines will drop out of the bottom of the truck and form small dams in the gravel bed. Gravel should also have a minimum Mohs hardness of 6, which will also decrease production of fines during transit and placement.

Pea gravel placed on top will ease in the planting operations if larger rock is used as the media. The same principle as construction of sand filters applies when sizing materials. It is easier to plant in pea gravel than in 1.5 inch to 3 inch rocks. The use of larger rocks than those selected for the primary treatment media at the distribution and collection end of the system will assist in the equal distribution of wastewater in the influent and effluent.

Placement of gravel over a liner is a challenge. If the gravel is crushed, then the liner must be protected with a geotextile. In large projects, vehicles with large tires such as front-end loaders work well. The construction of a gravel road through the middle of the system that is at least 8 inches deep can provide a thoroughfare for bulldozers to push material.

Gravel should be placed level and be free of vehicular tracks, depressions, and ridges. The gravel bed can be filled with water to determine if the surface is level, and depressions then filled and ridges leveled.

5.2.3 Conceptual Design

In coordination with the information used to select the site of the constructed wetland, the conceptual design begins to define the progression of the constructed wetland and the physical makeup of the project. The conceptual design helps stakeholders visualize the completed wetland and serves to document the project. The conceptual design will move the project from technology selection in the feasibility study, through permitting, and to a preliminary design. Its development will be an outgrowth of the data and analysis from the feasibility study, including treatability testing. Permitting, which includes detailed analysis of applicable regulations and discussions with regulators, will lead to a preliminary design after appropriate changes and iterations of the conceptual design. The conceptual design will become a tool for specifying project requirements as they evolve. Negotiations with regulators will further clarify and define unknowns.

5.2.4 Treatability Studies

Due to variability of the water to be treated and differences between theoretical performance and full-scale operations, adaptive management techniques should be anticipated. An example of an adaptive approach could include building a wetland that treats all or part of the water and monitoring its performance. If the system does not perform as designed, diagnostic monitoring can be performed to determine what needs to be changed. Changes can include reducing flow, adding additional nutrients, changing the inlet or outlet configuration (minimize preferential pathways, therefore, increasing retention time), or inducing recirculation of effluent back to the influent. An initial analysis up front should be performed to evaluate if the potential for negative impacts are small compared to the benefits of improving water quality. Almost all wetlands provide treatment, but they may not always provide consistent compliance. At some sites, for example at abandoned mine sites in remote locations, complete regulatory compliance may not be necessary to improve water quality and restore aquatic life to the impacted receiving waters.

During the initial phase, which could last from one to five years, the wetlands may not consistently meet standards, but the data gained during that period of time might be instrumental

for future design or evaluation of alternatives. Decision makers need to evaluate the risks associated with deferring decisions for treatment until adequate source characterization and performance data have been obtained or to invest in a system that might not be fully adequate. Even in a system that doesn't act as the final remedy, the reduction in loads and the data collected should still be valued.

5.2.5 Final Design

Before receiving the final permits, the final design must be prepared, reviewed, and approved by regulating agencies. Before the final design is completed, there may have been several regulatory meetings and conceptual design changes. For example, the addition of a public wildlife viewing area will require design changes. Ensure that the final design includes specifications of the inlet and outlet structures, seeding or planting requirements, and additional project startup needs. An operation and maintenance plan and monitoring strategy should also be included either before project startup or with the final design. Process design procedures for municipal and mine drainage treatment are discussed in detail below.

Design Issues Specific to Municipal Wastewater Applications

As described in Section 2 (Figure 2-1), SF wetlands for treatment of municipal wastewater may be conceptually divided into three pollutant removal zones:

- the initial fully vegetated zone where TSS removal and solid BOD removal take place through flocculation, sedimentation, or some anaerobic biodegradation
- the middle open-water zone where aerobic biodegradation of soluble organic constituents (BOD) and nitrification take place
- a second fully vegetated zone for polishing just prior to effluent discharge, where final reduction in TSS and nitrogen (via denitrification) take place

Removal of most of the TSS, particulate BOD, organic nitrogen and phosphorous, metals, and certain semivolatile organic compounds reaches completeness in the initial fully vegetated area within about two days. The depth of this zone should be between 0.6–0.9 meters (USEPA, 2000).

Reaeration occurs in the open-water area, supplying oxygen for oxidation (aerobic biodegradation) of soluble carbonaceous material (BOD) and facilitating the nitrification of NH_4-N to NO_3-N. Removal of pathogens (fecal coliform) occurs here through disinfection by sunlight. However, there may be an input of fecal coliform (FC) and other contaminants from waterfowl. Additional input of soluble BOD may enter this zone from anaerobic degradation of settled organic matter. The removal rate of soluble BOD and FC are temperature-dependent and first-order degradation rate equations can be used to design the size of this zone. The maximum HRT in this zone is generally limited to 2 to 3 days at maximum flow rate (Qmax) before unwanted algal blooms may occur (USEPA, 2000). The algal blooms cause increase in pH, interfere with FC kill and growth of submerged plants, increase NH_3-N volatilization, and induce phosphorus precipitation. The additional biomass and precipitates represent additional internal loading that must be removed in the next zone. Increasing the size of the open-water zone

generally increases DO, pH, and NO_3-N while decreasing soluble BOD and ammonium (USEPA, 2000). If additional area is required for the reactions to reach completion, additional open-water areas may be constructed. However, a fully vegetated zone should follow each open-water area. The result is a five-compartment wetland (instead of three zones). The open-water depths should be between 1.2 and 1.6 meters.

Given that denitrification is temperature-dependent, a HRT of 2 days at Qmax is generally sufficient for the anaerobic denitrification reactions to reach completion in the pre-exit vegetated areas (USEPA, 2000). Temporary nutrient (phosphorous and nitrogen) removal by plant uptake may be significant at certain times of the year, but release of these nutrients occurs at other times and may mask the removal effects of the processes occurring in this zone.

The design criteria for SF wetlands are presented in Table 5-1. To meet secondary effluent standards, BOD loading in SF wetlands should not exceed 60 kg/ha-d (6 g/m^2-d) maximum monthly loading rate. TSS loading, which generally controls wetland size, should not exceed 50 kg/ha-d (5 g/m2-d). The main failure mechanisms are short-circuiting and high flow velocities, leading to inadequate hydraulic retention time (HRT) for contaminant removal to take place and high TSS, both of which may exceed effluent discharge limits.

Table 5-1. Recommended Design Criteria for SF Constructed Wetland

Parameter	Design Criteria
Effluent Quality	BOD & TSS effluent: 20 or 30 mg/L
Pretreatment	Oxidation ponds (lagoons)
Design flows	Qmax (max monthly flow) Qave (average flow)
Max BOD loading (to entire system):	45 kg/ha-d (40.1 lb/ac-d) for 20 mg/L effluent 60 kg/ha-d (53.4 lb/ac-d) for 30 mg/L effluent
Max TSS loading (to entire system):	30 kg/ha-d (26.7 lb/ac-d) for 20 mg/L effluent 50 kg/ha-d (44.5 lb/ac-d) for 30 mg/L effluent
Water depth	0.6–0.9 m for fully vegetated zone, 1.2–1.5 m for open-water zone, 1.0 m for inlet settling
Minimum HRT (at Qmax) in 1 (&3)	2 days (fully vegetated zone)
Maximum HRT (at Qave) in 2	2–3 days (open water)
Minimum number of cells	3 in each treatment train
Minimum number of trains	2 (unless very small).
Basin geometry (aspect ratio)	Optimum: 3:1 to 5:1; AR > 10:1 may need to calculate backwater curves
Inlet settlings	Where pretreatment fails to retain settleable particulates
Inlet structures	Uniform distribution across cell inlet
Outlet structures	Uniform across cell outlet

Parameter	Design Criteria
Outlet weir loading	< 200 m^3/m-d (<16,108 gpd/ft)
Vegetation — emergent	*Typha* or *Scirpus* (native species preferred)
Vegetation — submerged	*Potamogeton*, *Elodea*, etc.
Design porosities	0.65 for dense emergent species in fully vegetated areas, 0.75 for less dense stand of emergent species, 1.0 for open water areas
Cell hydraulics	Each cell should be completely drainable. Flexible intercell piping to allow for required maintenance. Independent single-function cells could maximize treatment.

(Source: USEPA, 2000)

Maximum loading rates may also be used to calculate the size of zone 1 (the initial fully vegetated zone at the influent end of the SF wetland) and then determine if adequate hydraulic retention time (two days) is available at maximum monthly flow rate. These loading rates are 40 kg/ha-d (4 g/m^2-d) BOD and 30 mg/ha-d (3 g/m^2-d) TSS based on maximum monthly influent rates. The areal loading rates in the above table are for the entire wetland system.

Using the recommended areal loading rate and the influent contaminant loading, the size of the SSF wetland can be determined. TSS removal is good at loading rates less than 20 g/m^2-d based on maximum monthly influent TSS (USEPA, 2000). BOD removal is not as good as TSS and usually controls the design requirements to meet secondary standards (30 mg/L effluent concentration). BOD removal is good at loading rates less than 6 g/m^2-d based on maximum monthly influent BOD (USEPA, 2000). SSF wetlands can be effectively used to treat secondary effluents so the system consistently meets secondary standards by limiting the BOD ALR to a maximum monthly value of 8 g/m2-d (71 lb/ac-d) (USEPA, 2000). The recommended design criteria for SSF constructed wetlands are summarized in the table below (Table 5-2).

The main failure mechanism for SSF wetlands is related to media clogging and the resulting surfacing of untreated water. USEPA (2000) noted that the media should be ¾ to 1 inch in average diameter, smooth, rounded, fairly hard material (Mohs hardness of 3 or greater), and not limestone (due to dissolution in strongly reducing environment of the SSF wetland). This recommended design differs from European designs that use finer sized media (sand-sized particles). The clean hydraulic conductivity (K) for this recommended media is approximately 100,000 m/d (3.28 x 10^5 ft/d), which varies over time in an operating SSF wetland due to solids accumulations, bacterial growth, and root growth. A conservative K value for design purposes has been recommended by USEPA (2000): 1% of clean K for the first one third of the SSF wetland and 10% of the clean K for the final 2/3 of the wetland length.

Table 5-2. Summary of SSF Wetland Design Criteria

Parameter	Criteria
Pretreatment	Recommended primary treatment—sedimentation (e.g., septic tank, imhoff tank, primary clarifier); SSF not recommended for use after ponds because of problems with algae (clogging).
Surface area	Based on desired effluent quality and areal loading rates as follows:
BOD	6 g/m^2-d (53.5 lb/ac-d) for 30 mg/L effluent
BOD	1.6 g/m2-d (14.3 lb/ac-d) for 20 mg/L effluent
TSS	20 g/m2-d (178 lb/ac-d) for 30 mg/L effluent
TKN	Use another process in conjunction with SSF.
TP	Not recommended for phosphorus removal.
Depth Media Water	 0.5–0.6 m (20–24 inches) 0.4–0.5 m (16–20 inches)
Length	As calculated; minimum of 15 m (49 feet)
Width	As calculated; minimum of 61 m (200 feet)
Bottom slope	0.5%–1 %
Top slope	Level or nearly level
Hydraulic conductivity, K_h First 30% of length Last 70% of length	 Use 1% of clean K_h for design calculations. Use 10 % of clean K_h for design calculations.
Media Inlet—1st 2 meters (6.5 feet) Treatment Outlet—last 1 m (3.2 ft) Planting media—top 10 cm (4 inches)	 40–80 mm (1.5–3 inches) 20–30 mm (0.75–1 inch) 40–80 mm (1.5–3.0) 5–20 mm (0.25–0.75 inches)
Miscellaneous	Use at least 2 SSF wetlands in parallel. Use adjustable inlet device to balance flow. Use adjustable outlet device to balance flow.

(Source: USEPA, 2000)

The design procedure is summarized as follows:

1. Determine the total surface area using recommended ALR for each pollutant, and choose the larger area requirement, then find the area of each treatment.
2. Determine the width using Darcy's Law applied to the initial treatment, considering the maximum allowable head loss is 10% of the media depth and considering the area calculated above.
3. Determine the length and head loss using Darcy's Law.
4. Determine bottom elevation using recommended bottom slope.

5. Determine water elevations throughout the SSF wetland using head loss.
6. Determine water depths accounting for bottom slope and head loss.
7. Determine required media depth.
8. Determine the number of SSF wetland cells.

Design Issues Specific to Mine Drainage Applications

The type of wetland constructed to treat mine drainage is determined by the quality of the input water. Although net acidity and alkalinity are used to select the general type of wetland, the details of the design are determined by the removal needed to meet effluent levels and by the initial concentrations of iron, aluminum, sulfate, and trace metals.

SF wetlands can be used to treat water that is net alkaline. These wetlands are also called aerobic wetlands, since most of the treatment occurs in the oxygenated or aerobic portion of the wetland. Aerobic constructed wetlands used to treat mine drainage typically consist of shallow excavations filled with flooded gravel, soil, and organic matter to support wetland plants, primarily *Typha* but other species including *Juncus* and *Scirpus* have also been used (Skousen et al., 1998). These systems also contain oxidizing bacteria, such as *Thiobacillus ferro-oxidans, Leptothrix discophora*, and *Ulothrix* (Robbins, 1999). The cells are typically on the order of 30 cm (12 inches) deep or less and lined with relatively impermeable sediments composed of soil, clay, or nonreactive mine waste.

Biogeochemical interactions provide treatment as contaminated water travels through the constructed wetland, typically across the surface or near surface. Aerobic wetlands promote oxidation and hydrolysis in the surface water of the wetland, which is the primary removal mechanism for iron. Areal removal rates for iron in these systems generally vary between 10 and 20 grams/m^2/day (Hedin et al., 1994).

Often a net acid drainage can be converted to net alkaline by using either an anoxic limestone drain or sequential alkalinity-producing wetlands (SAPS) (also called reducing alkalinity-producing wetlands, RAPS). Anoxic limestone drains (ALDs) are buried cells or trenches of limestone into which anoxic (oxygen-free) water is introduced. The limestone dissolves in the mine water and adds alkalinity. Under anoxic conditions, the limestone does not coat or armor with Fe hydroxides because ferrous iron (Fe^{+2}) does not precipitate as $Fe(OH)_2$ at pH <8.0. The effluent pH of ALDs is typically between 6 and 7.5. The sole function of an ALD is to convert net acidic mine water to net alkaline water by adding bicarbonate alkalinity. The removal of metals within an ALD is not intended and has the potential to significantly reduce the permeability of the drain resulting in premature failure. Once the drainage has been converted to net alkaline, it is typically treated with a settling pond and a surface flow wetland.

A sequential alkalinity-producing system (SAPS) looks like a vertical flow wetland. The system contains a bottom layer of limestone, which is covered by about 15–30 cm of organic material, whose function is to remove oxygen from the water. Once the oxygen is removed, iron will be reduced from ferric (Fe^{+3}) to ferrous (Fe^{+2}) and the underlying limestone will function much like an anoxic limestone drain. The limestone will dissolve and increase the alkalinity of the drainage without armoring with iron hydroxide precipitates. The discharge from the SAP system is

directed to a settling pond and/or a surface flow wetland where the iron is removed by precipitation. Depending on the initial acidity of the drainage, more than one cell may be needed to increase the alkalinity to an acceptable level. More information on anoxic limestone drains and sequential, or reducing, alkalinity-producing systems can be found in publications by Skousen et al. (1998) and in Watzlaf et al. (2003).

SF wetlands can also be used to polish the effluent from anaerobic sulfate-reducing cells, which is typically low in dissolved oxygen and can contain elevated concentrations of dissolved sulfide. During system startup, BOD, fecal coliform bacteria, and color are also usually elevated. Aerobic cells can also contain cyanide-degrading bacteria that include *Actimomyces*, *Alcaligenes, Arthrobacter, Bacillus, Micrococcus, Psuedomonas*, and *Thiobacilus* (Canty et al., 2000).

SSF are often called anaerobic wetlands since treatment occurs in the deeper layers of the wetland where no oxygen is present. Constructed anaerobic (both vertical and horizontal flow) wetlands rely on various bacteria to remove iron, aluminum, manganese, trace metals (e.g., copper, lead, zinc, cadmium, chromium, cobalt, uranium), sulfate, selenium, cyanide, and nitrate. The SSF wetland is often constructed of a mixture of organic/nonorganic materials and may include woody waste, compost, manure, hay, limestone, and a bacterial starter culture, or inoculum, which is typically a suite of indigenous bacteria rather than a specific bacterial strain that was nurtured in a laboratory environment. The consortium of bacteria and the degree of reductive environment is dependent upon the amount and type of carbon available and the electron donors.

In anaerobic constructed wetlands designed for heavy-metal removal, the metabolic products of sulfate-reducing bacteria (SRB), in conjunction with the dissolution of limestone, which is generally included as part of the matrix of the wetland, are responsible for raising pH and precipitating metals as sulfides, hydroxides, and/or carbonates.

Certain bacteria, *Desulfovibrio* and *Desulfotomaculum*, can utilize reactions between organic substrate (CH_2O, a generic symbol for organic carbon) and sulfate as a source of energy for their metabolism. The bacteria require relatively simple organic compounds, so only part of the organic matter is normally usable by them, or they require action by fermenting or other bacteria to degrade complex compounds. The bacteria convert sulfate to sulfide, which can react with the metals in the drainage to form metal sulfide precipitates.

$$SO_4 + 2CH_2O = H_2S + 2HCO_3 \qquad (1)$$

$$H_2S + M^{+2} = MS + 2H^{+} \qquad (2)$$

If there is an excess of sulfate reduction, bicarbonate alkalinity will be produced and pH will increase.

Sulfate-reducing bacteria are ubiquitous and tolerate a wide range of environmental conditions (Postgate, 1984). Their optimal pH range has been reported to be from 5 to 9, but they can control their microenvironment even when the bulk solution pH is below 5. Sulfate-eduction

treatment has been successful even when the pH of the drainage was below 3 (Bolis et al., 1991; Gusek, 1998).

Alkalinity can also be generated as the limestone, which is generally incorporated with the organic material, reacts with acidity in the drainage:

$$CaCO_3 + H^+ = Ca^{+2} + HCO_3^- \qquad (3)$$

The limestone continues to react when kept in an anaerobic environment because ferrous iron is relatively soluble at pH 7 in anoxic water and ferrous hydroxide does not form and coat the limestone.

One criterion for sizing anaerobic wetlands is the rate of sulfate reduction (Eger, 1994). For sulfate reduction to be successful in treating acid drainage, the rate of sulfate reduction (Equation 1) must be greater than or equal to the rate of metal input. If the rate of sulfate reduction exceeds the rate of metal input, excess alkalinity is generated and the pH of the drainage increases. If the sulfate-reduction system was 100% effective at removing metals, then one mole of sulfate would be reduced for each mole of divalent metal precipitated (Equations 1and 2). The removal of each mole of aluminum and ferric iron requires 1.5 moles of sulfate reduction (Dvorak et al., 1992; Eger, 1992). Therefore, to remove all the metals and acid in the input, the required rate of sulfate reduction can be calculated from:

$$\begin{array}{ll} \text{Required rate of} & \sum \text{mmole divalent metals } (M^{+2}) \\ \text{sulfate reduction} = & + 1.5 \sum \text{mmole } Al^{+3}, Fe^{+3} \\ & + 0.5\,(1000 \times 10^{-pH}) \end{array}$$

where:

the rate is in millimoles/day, and
the metal load is computed by multiplying the concentration in mmoles/l by the flow in l/day.

In order to maintain a healthy population of sulfate-reducing bacteria, the pH in the bacterial microenvironment must be maintained in the range 5 to 9. In order to sustain this type of environment, the rate at which acidity is applied to the system must be less than the wetland's ability to neutralize this acidity. If the rate of acidity input exceeds the neutralization capacity of the system, pH will decrease and sulfate reduction will stop (Eger, 1994).

Sulfate-reduction rates, expressed as millimoles per unit volume of substrate per day, have been reported to range from 0.1 to more than 1 mmoles/m^3/day (100 to 1000 mmoles/m^3/day). The actual rate will be a function of the type and age of the organic carbon source and the temperature. Wildeman et al. (1993) proposed that a rate of 300 mmoles/m^3/day be used as a design rate.

An estimate of the volume of substrate required can be calculated from:

$$\text{Required rate of sulfate reduction} = \sum \text{mmole divalent metals } (M^{+2}) + 1.5 \sum \text{mmole } Al^{+3}, Fe^{+3} + 0.5\,(1000 \times 10^{-pH}) < R \times V$$

where:

R is the rate of sulfate reduction for the substrate and conditions at the site (millimoles/m^3/day), and
V is the volume of substrate that will be needed (m^3).

This simple balance works well when the pH of the input drainage is within the optimum range of the sulfate-reducing bacteria. If the pH is low, Gusek and Wildeman (1998) recommend spreading the input water over a larger area to avoid removing all the neutralizing capacity in the top of the substrate. More inorganic alkalinity (e.g., limestone) could also be added to the substrate. Since there is essentially no mixing in the substrate, if the acid load per unit area is too high, the pH in the top of the wetland will decrease to the level of the input and sulfate reduction will cease. Based on empirical evidence, Gusek (personal communication, 1998) recommended that the area required should increase as pH decreases. The area ranges from around 9.8 m^2/ liter/min for near neutral drainage to 19.6 m^2/ liter/min for the typical acid mine drainage with a pH of 3 to 4. These rates are in general agreement with the value of 3.5 g acidity/m^2/day proposed by Hedin et al. (1994).
In many subsurface systems, the carbon source for the bacteria is provided by the organic substrate included in the wetland. Recently, subsurface wetlands have been modified or constructed so that the food source is added along with the drainage to be treated. This design provides a consistent food source, and systems can be built without an organic substrate, providing better flow characteristics and system control (Tsukamoto and Miller, 1999; Anderson, 2001).

By adding the carbon source to the wetland system, the wetland should not lose efficiency as the substrate ages and becomes less reactive. A decrease in reactivity up to 50% has been reported for some systems after about three years of operation. With substrate-based systems, initially much of the carbon present in the substrate is readily available to the bacteria. As the system ages, the remaining carbon is harder to break down (more refractive), and the rate of reaction slows (Tarutis and Unz, 1994).

Although the major concerns with constructed wetlands (longevity, winter operation, substrate disposal, and movement of contaminants into the food chain) are similar for all applications, there are some specific concerns related to mining applications. The parameter being treated and the type of process responsible for the treatment affect longevity. For example, the lifetime of wetlands constructed to remove iron from net alkaline mine drainage is determined primarily by the rate of accumulation of iron precipitate and the total size of the wetland. For coal-mine drainage where the primary contaminant is iron, work is being conducted to examine the feasibility of recovering the iron and using it as a pigment in paint (Hedin, 1998, 2001). Wetlands removing trace metals with removal based primarily on adsorption, ion exchange, and chelation have a capacity based on the uptake potential of the substrate, while the lifetime of anaerobic wetlands is based on the availability of small chain organic compounds that fuel the

sulfate-reducing bacteria. Although there are still unanswered questions on the lifetime of constructed wetlands, several successful systems have been operating for nearly 10 years or more (Case Study #28; Eger et al., 2002; Stark et al., 1994).

A summary of design criteria for wetland systems used to treat mine drainage is presented in Table 5-3, which is adapted from Skousen (1998).

Table 5-3. General Design Guidelines for Wetlands Constructed to Treat Mine Drainage

Treatment System	General Requirements	Construction	Design Factors	References
Surface flow, Aerobic wetland	Net alkaline water	Overland flow Cattails planted in substrate	Areal removal rates • 10–20 g Fe/m ^{2} /d • ·0.5–1 g Mn/ m ^{2} /d	Hedin et al., 1994
Subsurface flow Horizontal-flow Anaerobic wetland	Net acidic water, generally low flow rate	Horizontal flow above organic substrate	• Areal removal rate 3.5 g acidity/ m ^{2} /d • Hydraulic conductivity of substrate, minimum 10 $^{-3}$ –10 $^{-4}$ cm/sec • Rate of sulfate reduction (~300mmoles/m ^{3} /day) • Hydraulic loading	Hedin et al., 1994; Wildeman et al., 1993
Subsurface flow Vertical-flow Anaerobic wetland	Net acidic or alkaline water	Vertical flow through organic substrate, or an inorganic substrate with carbon food source added to input	• Rate of sulfate reduction (~300mmoles/ m ^{3} /day) • Hydraulic loading • Area requirement • pH 7; 10 m^2/l/min • pH 3–4; 20 m^2/l/min	Wildeman et al., 1993; Eger, 1994; Eger and Wagner, 1995, 2001; Gusek and Wildeman, 1998
Anoxic Limestone Drain (ALD)	Net acidic water DO<1.0 mg/L Fe 3+ <1.0 mg/L Al <1.0 mg/L	Horizontal flow through buried limestone	• 15 hours contact time • 6–15 cm diameter limestone • Lifetime limestone consumption	Hedin and Watzlaf, 1994
Successive alkalinity-producing systems (SAPS) or Reducing alkalinity-producing systems (RAPS)	Net acidic water	Vertical flow through an organic layer overlying a limestone bed	• 15–30 cm organic matter with adequate permeability • 6–15 cm diameter limestone • 15 hours contact time in limestone • Lifetime limestone consumption	Watzlaf et al., 2003

(Modified from Skousen, 1998)

6.0 CONSTRUCTION, OPERATION, AND MAINTENANCE

6.1 Construction

Regardless of the objective of the treatment wetlands, from a construction standpoint the operative point is to consider that the three parameters of soil, hydrology, and vegetation must be introduced to facilitate the establishment of wetlands. The key parameter required to ensure the success of the constructed wetlands is the hydrologic parameter. The wetlands must be designed and constructed to ensure periodic saturation necessary for the establishment of wetland plants, as well as allow adequate retention to remove inorganic constituents, organic chemicals, nutrients, or pathogens that might be the targeted components within the waste stream. The findings of the previously described water budgeting process must be incorporated into the design process to ensure the successful establishment of the wetlands. Depending upon the nature of soils within the vicinity of the construction site, either clay or a synthetic barrier such as a HDPE plastic may be required to act to retain water within the system and prevent downward percolation.

Following site preparation and grading, appropriate backfill must be used to serve as a medium for plant establishment. Backfill may vary from topsoil to subsoil depending on the application and the design requirements. Generally, hydric soils need not be used as fill material. With the placement of fill in areas under wetlands' hydrologic regimes, hydric parameters will develop over time. The organic content typical of wetland soils will develop as a function of both aboveground and belowground plant production, which again is a function of the wetlands hydrology. Additionally, the use of hydric soils as fill can lead to the introduction of undesirable vegetative species into the construction area, depending on the location from where the soils were obtained. However, this consideration can be mitigated to some extent through careful selection of the source area for the soil.

The vegetative community in the constructed wetlands will be placed in a manner such that both the biological and treatment functions of the wetland are enhanced. The wetland will be planted with appropriate species depending upon the climatological setting of the site, as well as the objectives of the constructed wetland.

6.1.1 Soil Erosion and Sediment Control

Prior to the commencement of any construction activities that will disturb existing soils at the proposed site of the constructed wetlands, or adjacent thereto, soil erosion and sediment control measures shall be constructed in accordance with relevant state standards for soil erosion and sediment control. The primary objectives will be to prevent sediment from being washed from the excavated areas into undisturbed areas. All soil erosion and sediment control measures should be maintained in good condition and left in place until permanent vegetation is established.

6.1.2 Grading and Subgrade Preparation

Prior to grading or other construction activity, the construction location should be cleared of all vegetation and debris. All cleared vegetation should be chipped and temporarily staged with other debris in an upland area. Chipped material can serve as mulch for planting operations. Non-recyclable material should be disposed of at a landfill. The limits of possible excavation should be marked to minimize the potential for indirect impacts to surrounding areas.

Following clearing, the constructed wetlands site should be excavated to the contours outlined in the detailed specifications prepared during the design process. Cross-sectional drawings and contour drawings showing the current and finished grades should be utilized. Cross sections should be established through the construction area at a minimum of fifty yard intervals and show the current grade in all cardinal directions. Following removal of the topsoil, the subsoil material should be removed to a rough grade, approximately 6 to 12 inches below the final grade consistent with planned elevations. If specifications call for an impermeable barrier, allow sufficient room in the excavation for placement of such a barrier. Inspections should be made on a periodic basis (at a minimum of 24 hours) of the conditions of the earthwork. At the completion of the soil excavation to the rough grade, a final inspection of the grades should be made.

Preparation of the subgrade is a crucial part of the construction process. It is extremely important that the subgrade be properly compacted to a design density to reduce settling under the liner and avoid stress. Some soils will not support this weight without deformation; this should be considered when locating the wetlands.

It is essential that some grading tolerance specifications be included. Rough grades, before placement of liner materials, should be graded level or have a uniform gradient that is within +/- 0.1 foot. Heavy construction equipment must be kept off rough grades if the compacted subgrade is unable to support the vehicle weight without deformation. Finish grades, gravel or soil, should be graded to within +/- 0.05 foot.

Geotextiles are highly recommended if the subgrade cannot be prepared to the standards described previously. Geotextiles are easier to place than sand and have the advantage of staying on sloped berms. The following general design guidelines for use of geotextiles should be considered:

- No geotextile is required where rocks are less than 3/8-inch-diameter.
- If visible rocks are less than ¾-inch-diameter, 4-oz nonwoven polyester or polypropylene geotextile fabric should be placed on the subgrade to protect the liner from punctures.
- If the rocks are larger than ¾-inch-diameter and smaller than 1.25 inch-diameter, then an 8-oz geotextile should be used.
- Rocks larger than 1.25-inch-diameter should be removed, or a 6–12 inch underlayment of sand should be placed on the subgrade to prevent the bridging of the liner material over the rocks.

To establish the topographic contours of the constructed wetlands to final grade after rough grading or liner placement, suitable substrate (at least 6 to 12 inches deep) may be brought in. Topsoil for backfilling should consist of a soil suitable for supporting plants in that region, contain organic material to meet design specifications (typical 8% to 12% organic carbon content), and be readily available. The target pH for the soil should be 6 (± 1 standard unit). If the wetland is constructed on a compacted clay or plastic liner, soil will have to be placed on the liner so that the finished surface is level and free of vehicular tracks.

6.1.3 Plants and Plant Installation

The design specifications will identify those wetland vegetative species to be installed in the constructed wetland. The selection of the particular species will be based on the type of effluent being treated, the biogeographic distribution of a species, design considerations such as longevity and climate, and aesthetic requirements such as wildlife habitat or environmental interpretation. In general, constructed wetlands will make use of herbaceous species. Woody species may be used to some degree; however, that usage is based more on habitat considerations.

Grid spacing will generally be used for plant installation, though individual species can be randomly offset from each grid node to create some heterogeneity. A typical spacing is two feet between individual plants. Broadcast seeding can be used to supplement the plantings.

Once the soil is in place and the plants have been planted, water should be increased gradually to match plant growth. For very long cells, intermediate, temporary soil dikes should be constructed to maintain water level as planting takes place. Planting should begin at the outlet and progress via these temporarily constructed dikes toward the front.

6.1.4 Postconstruction Activities

Following completion of the constructed wetlands, an as-built report detailing all construction activities should be prepared and submitted to federal, state, or local regulatory agencies involved in overseeing the construction process. Included in the report should be the notes and observations collected by the on-site supervising engineer during grading and planting activities. The report should include maps, data sheets, photographs, and available water budget data. Other postconstruction activities include activities specified in the operations and monitoring sections outlined below.

6.2 Operation and Maintenance

Whether the need for a maintenance activity is identified during the periodic vegetative monitoring or through casual, routine observations of the site, certain actions will be necessary to ensure the efficacy of the constructed wetlands. An operations and maintenance (O&M) plan should be prepared during the planning process to outline those actions to be used in the maintenance of the wetlands.

Potential maintenance activities (as further specified in USEPA, 2000) include maintenance of water flow uniformity (inlet and outlet structures), management of vegetation, odor control, control of nuisance pests and insects, and maintenance of berms and dikes and other constructed water control structures.

Regardless of the waste stream or the treatment objective, O&M requirements are very similar. Water-level control is the most critical operational parameter as this activity ensures the function of the system as a wetland. Berms must be periodically inspected to ensure their integrity. Significant changes in water levels must be investigated immediately to ensure that a breach in the berm or dike system containing the wetland has not occurred as a result of storm damage or clogged drainage pipes. Proper maintenance of inlet and outlet piping will ensure that these structures do not clog, thereby ensuring both proper water level and water flow. Maintenance activities associated with removing clogs and/or debris include physical removal of trapped sediment, periodic flushing of pipes and manifolds, and the use of high-pressure water sprays for periodic cleaning.

A significant potential maintenance activity is the control of nuisance pests, which include beavers, muskrats, mosquitoes, and other biting insects. Because wetlands contain standing water for extended periods of time, they are perfect breeding grounds for mosquitoes. In sufficient number, mosquitoes can be an extreme nuisance to humans and may transmit debilitating, sometimes fatal, diseases to humans and livestock. Therefore, the management of constructed wetlands must take into account the possibility that mosquitoes will thrive in these settings and take measures to limit their impact. It must be noted, however, that scientific research does indicate that the actual incidence of mosquito-related problems associated with wetland treatment systems is rare.

The literature suggests that most mosquito problems in treatment wetlands are associated with excessive organic loadings in the system. Control of mosquito populations can be addressed through the reduction or management of organic loadings, which maintains dissolved oxygen levels and supports the establishment of mosquito larvae predators. Bats and birds may be helpful in controlling mosquito populations. Some control over mosquitoes can be managed through water-level management and an increase in water flow through the system. While not preferable, pesticides can be used under certain circumstances to control mosquito populations.

One of the simplest ways to control mosquito populations is through the introduction of mosquitofish (*Gambusia affinis*) into the wetland system. However, mosquitofish require perennial flooded areas and cannot tolerate strongly anoxic conditions. Additionally, mosquitofish are not tolerant of cold weather and will not survive in northern climatic regions.

6.3 Monitoring Constructed Wetlands

Monitoring is needed to measure system performance and discharge compliance, maintain wetland operational control, and allow the identification of performance trends that might develop into problems early on when intervention is most effective. A written monitoring plan is essential if continuity is to be maintained throughout the life of the project, which may span decades. Regulators will probably insist on an agreed-upon monitoring plan prior to permit

submittal, or they will add permit conditions requiring specific monitoring activities. Additional regulatory monitoring may be required depending on the nature of the project (i.e., research or compliance).

Typically, monitoring requirements are listed in the NPDES permit for the project. In general, it is recommended that all inflow and outflow points on the wetland treatment system be monitored for temperature, dissolved oxygen, pH, and conductivity on a weekly basis. For constructed wetlands treating municipal wastewater, monthly monitoring of biochemical oxygen demand, total suspended solids, chloride, and sulfate should be added on a monthly basis. For constructed wetlands addressing industrial streams, monthly monitoring of chemical oxygen demand and total suspended solids should be added on a monthly basis. For stormwater systems, total suspended solids should be monitored on a one-storm-event-per-month basis. Water flow within the wetland should be monitored daily, as should rainfall and water stage. Plant cover for dominant species should be monitored on an annual basis. As determined in the waste characterization stage, organic and inorganic contaminants, as well as toxicity, should be measured on a quarterly basis.

It is recommended that at a minimum a monitoring plan should rely on standard soil and water analytical techniques to generate the necessary data to show that the constructed wetland system is performing. These primary lines of evidence can then be supported with additional analytical techniques to address contaminant fate and transport in the plant tissues, root penetration, and transpiration rates. Additional monitoring of the plant tissues is often required to ensure that the plants are not posing any environmental risks, particularly to other ecological receptors (i.e., transfer to the food chain). The analytical methods to monitor system performance should be approved in the planning stages of the project. If the application for system approval does not adequately address monitoring concerns expressed by regulators and stakeholders, the proposed system should not be approved.

6.3.1 Performance

Depending on wetland size, the quality of incoming water, and the flow rate, a constructed wetland may or may not be capable of meeting certain treatment goals. In cases where a constructed wetland alone is impractical, perhaps from high contaminant concentrations or recalcitrant chemicals, a constructed wetland may be used in conjunction with other treatment methods. A wetland is sometimes constructed as part of a treatment train, which can include a number of unit processes in series such as settling ponds, oil/water separators, and physical/chemical treatment methods.

Since wetlands are natural, biological systems, background levels of certain water quality parameters at steady-state equilibrium could be above desired effluent levels in some cases. In these cases, removal below effluent goals becomes impractical without some form of additional treatment. One common example is the presence of coliform bacteria. Waterfowl and other animals may frequent SF wetlands and introduce bacteria to the water. Consequently, in some cases the natural levels of fecal coliform in wetlands may exceed treatment goals or permit conditions. Occasionally post-treatment such as chlorination and dechlorination may be

necessary. Disinfection by chlorination will kill off enough additional bacteria to achieve the regulatory requirement.

A similar issue exists with dissolved oxygen levels, a commonly regulated parameter. Natural wetland processes consume oxygen, which can make dissolved oxygen levels of wetland effluent so low that aeration of the effluent may be required. The solution may be as simple as including a cascading drop over rocks at the exit point of the wetland. Nevertheless, it is important to remember that in some cases wetland treatment alone might not be sufficient to meet all receiving water goals.

Wetlands designed for groundwater discharge entail different treatment goals. They avoid the potential problems of discharging to receiving surface water bodies, while at the same time recharging aquifer supplies. Potential impacts to groundwater must be carefully assessed. It is particularly important to monitor nitrate/nitrite levels in such situations since these nitrogen forms can adversely impact potable aquifers. Planners must also consider other contaminants that might be present in wastewater sources, such as heavy metals and pesticides, when discharging to groundwater.

7.0 COSTS

A variety of factors affect the cost of constructed wetlands:

- detention time (climate dependent),
- treatment goals,
- media type (deeper systems require less liner),
- pretreatment type,
- number of cells (more cells require more hydraulic control structures and liners),
- source and availability of gravel media, and
- terrain.

Due to the wide range of design possibilities, some standardized basis for comparison must be established, including construction cost versus detention time (HRT) and construction cost versus daily volume treated.

Additional complications in providing good comparative cost information include separating different design goals such as BOD removal versus BOD and nitrogen removal. Effluent BOD design goals will also affect detention times. For example, designing for an effluent BOD of 30 mg/L versus an effluent BOD of 10 mg/L doubles the required area.

Detention time is a good means of comparison because of the different depth designers have used. Design depths typically range from 12 to 30 inches. As an example, a system designed with a 12-inch-depth versus a 24-inch-depth requires twice the area.

Economic efficiencies can be measured in other terms such as mass of BOD removed per day. Another useful comparison is energy costs, as suggested originally in Table 8-6 of USEPA's *Process Design Manual: Land Treatment of Municipal Wastewater* (USEPA, 1981). Whichever method is used, this final caveat must be recognized: a wetland is a temperature-sensitive technology (see Case Study #8 from Brighton, Ontario), and comparing system costs in Nebraska to system costs in Florida is like comparing the price of corn to that of oranges. Ultimately, cost comparisons should be based on systems with similar discharge limits and located in similar climates. When reviewing costs, engineers must consider other factors such as the number of cells and scale. For example, four cells totaling 1 acre cost more to build than one cell totaling 1 acre; large systems cost less per gallon than small systems.

Pretreatment has a major effect on wetlands construction costs. If the collection system is a small-diameter sewer system with interceptor tanks, pretreatment produces influent BOD about 120–140 mg/L with anaerobic properties (USEPA 1980, Table 4-1). Influent TSS is averaging 30 mg/L in some of these small-diameter systems. Compare this to a partial mix aerated lagoon and constructed wetland where the influent BOD is typically 30–60 mg/L and TSS is 75 mg/L.

The first system will require additional treatment steps if nitrogen removal is part of the design goal. Anaerobic pretreatment will produce nitrogen principally as ammonia, which will not nitrify very efficiently in SSF wetlands, especially in cold weather. However, aerobic pretreatment (in an aerated lagoon) produces nitrogen principally as nitrates, which are easily denitrified in SSF wetlands. The total energy cost of the second system is considerably higher

than the first, but the capital cost would be significantly less. Obviously, both total system costs and treatment goals must be considered.

7.1 Capital Costs

Wetlands costs can be broken down into the following components: excavation, liner, gravel, plants, distribution and control structures, fencing, and other. Given equal detention times, three of these components clearly encourage deeper designs. As wetlands get deeper, gravel and excavation costs remain stable, but—since area is reduced—less liner, fewer plants, and less perimeter fencing are required. Design depth also affects heat losses and winter-time performance. However, deeper design depths may affect treatment efficiencies.

Costs summarized in this section are from the following sources:

Bid tabs from Southwest Wetlands Group, Nolte & Associates
- Means “Heavy Construction Cost Data, 1995”
- Regional and local suppliers/installers of liners, gravel, and plants

For plant pricing
- Aquatic and Wetlands Nurseries, Rocky Mountain region and Southwest
- J.F. New and Associates, Midwest
- Envirotech Nurseries, Midwest

For liner pricing and installation
- Snow and Company, Southwest
- Environmental Liners, national
- Ted Miller & Associates, Rocky Mountain region

For gravel pricing
- Western Mobile, Western states

The single most important factor affecting capital cost is the cost of gravel, followed by the cost of the liner material. Material costs for both items increase as specifications become more severe. As a rule, gravel is 40–50% of the cost of a system for a 50,000-ft^2 system, with the percentage increasing as the system gets larger. The reason for the increase is that other costs decrease proportionately as the system gets larger. For example, the area of the perimeter run-out material in the liner decreases as percentage of the total area. Perimeter fencing costs decline for the same reason that liner costs decline.

Gravel usually costs about \$9.50/ton or \$13.00/yd^3 throughout the United States. Hauling costs can add significant amounts to the project, and delivered costs can exceed \$20/yd^3. There are also many areas in the United States where gravel is very costly or just not available. Some states, Florida for example, are considering the use of recycled concrete rubble.

Liners generally run 15–25% of the total cost, with this percentage declining as the system gets larger. The percentage rises as more expensive liner materials are used and the number of cells

increases. Soils with large (>1½ inches) angular rocks may require the use of an underlayment such as geotextile or sand. If design requirements dictate the need for geotextiles, costs will increase by 5–8¢/ft^2. If river run gravel is not available, sand or geotextile should be placed on top of the liner.

Liner costs are predicated on the quantity, thickness, and type of material specified. A good argument can be made for eliminating liners in certain soils with high clay content; but as regulators focus more attention on groundwater, reliance on use of in situ soils becomes problematic. Even with good soils in place, costs of testing and compaction can exceed the costs of a 30-mil PVC liner.

Liner costs have decreased significantly in recent years because of demand and because most liners are petroleum-based products. The current low prices could easily rise with oil prices, making clay soils and bentonite much more competitive. It is currently possible to get a 30-mil PVC liner installed for 38–40¢/ft^2 in small systems and 30–35¢/ft^2 in systems 100,000 ft^2 and larger. This price is generally available throughout the United States. Experienced liner crews will travel almost anywhere the job requires.

Table 7-1 provides good estimates of labor and materials costs for installed liners in areas greater than 100,000 ft^2, based on competitive bids by liner installers who have installed more than 2 million square feet. Prices are higher in the Northeast and California.

Table 7-1. Liner Costs for Areas Greater than 100,000 ft^2

Material	Thickness (mil)	Total cost, liner + installation (¢/ft^2)
PVC	30	30–35
PE	40	35–40
PPE	40	45–50
Hypalon	60	60–70
XR-5	NS	90
Reinforced PPE	45	55

The use of clay, clay with scrims, or in situ soils presents some problems that are usually site-specific and make estimating the costs of limiting percolation difficult. The addition of bentonite to the soil or the use of in situ clay soils is at first glance very simple. However, the additional costs of testing and compaction can add significant costs to the project. The costs associated with bentonite or in situ soils are often the same as installing a PVC liner. The engineer must carefully evaluate testing costs and additional time and equipment costs associated with mixing, wetting, and compaction.

Clay liners can be made of a thin layer of bentonite or, similarly, clay can be placed between two sheets of polyester fabric. Alternatively, polypropylene geotextiles have been used in landfill applications and in at least one SSF wetland. Clay liners with scrims have properties similar to

XR-5 and Hypalon or reinforced PPE, except for weight. Shipping can make this material more expensive than PVC; however, installation is very simple, and the resistance to chemical degradation is equal to that of Hypalon or XR-5. If shipping distances are reasonable, prices including installation have been quoted at 38–40¢/ft^2 (bid tab from mine tailings cap, Minturn, Colorado).

Excavation/earthwork is generally the third or fourth largest cost of a typical project. Obviously, this cost is terrain-dependent. Flat sites on sandy loam in Nebraska are easier to excavate than mountainside sites in Colorado. Consequently, SSF wetlands sites are usually constructed on level sites with good soils. As a result, excavation costs are usually about \$1.50–2.50/yd^3.

Plants are generally a minor cost. The plants used in SSF wetlands (cattails, reeds, and bulrushes) are generally available everywhere in the United States. Occasionally, they can be collected from local sources and planted in the constructed wetlands. In some cases, planting has been coordinated with county drainage ditch cleaning operations, reducing the cost of project plants to zero. Planting in gravel is easy: experienced crews plant 600–1000 plants per person per day. However, if the project must bear the costs of harvest, separation, cleaning, and transport to the job, plants are likely to be very expensive. The alternative is to seek wetlands nurseries capable of providing the quantity, species, and quality of plants the job requires.

Because of wetlands mitigation work, many nurseries throughout the United States can now grow and plant the plants used in constructed wetlands. The advantage of a nursery operation is that large quantities of viable plants 12–18 inches tall can be grown for ease of harvest and subsequently transplanted by hand or machine with a very high degree of success. Designers can expect >80% survivability. Costs for plants usually run about \$0.50–1.00 per plant, with most bids at the lower end. Many nurseries also grow plants on a contract basis for a particular project. By planning ahead, designers can obtain discounts on plants.

The question for the designer is plant spacing. Plants placed in 3-foot centers will each have to grow to fill 9 ft^2, while plants on 18-inch centers must fill only 2.25 ft^2. For a 50,000-ft^2 wetlands at 50¢ each, plants cost \$2,800 versus \$11,000 respectively. The problem for the designer is that a 20% loss at 3-foot centers means that there will very likely be large unvegetated areas. These will eventually fill in, but the project may not have the time to wait for the next growing season.

Historically, planting has been a casual affair, with success of the planting relying primarily on the hardiness of the plant species. Cattails and reeds, once started, are very aggressive and almost impossible to eliminate. Areas devoid of vegetation are not particularly important on large-scale SSF projects, but unvegetated areas on small projects need to be remedied as soon as possible. Replanting is a definite consideration and can be included in specifications requiring a minimum survivable population of plants. Experienced nurserymen are capable of meeting these types of specifications and can be called on to replant as part of their contract if necessary. The designer should expect the same type of performance on this part of the contract as from pump suppliers or liner installers.

Other minor costs include piping costs and level control structures, flow distribution structures, flow meters, and fencing. In addition, reseeding and erosion control costs should be provided for

in any design. Piping materials are generally plastics such as polycarbonate (PC), polyethylene, and acrylonitrile butadiene styrene (ABS), commonly available throughout the United States. Plumbing costs typically fall between 6% and 7%. Level control and flow distribution structures can be built of concrete block, cast-in-place and precast concrete, and for smaller systems, reinforced PC units are commercially available. Depending on the number of cells, these types of structures will usually run about 5% to 6% of the total cost.

Table 7-2 presents typical costs and should be considered similarly to the concept of standard construction units presented in cost-estimating handbooks. The caveats associated with this approach (e.g., site conditions, distance to gravel pit, liner requirements, and water quality) require another approach to estimating costs of constructing SSF wetlands.

Table 7-2. Cost of a Typical 50,000-ft^2 Subsurface Constructed Wetland

Component	Price/unit	Total ($)	%
Excavation/compaction	$1.75/yd^3	13,000	10.7
Gravel	$16/yd^3	51,900	42.6
Liner, 30-mil PC	35¢/ft^2	19,250	15.8
Plants, 18-inch centers	60¢/each	13,330	10.9
Plumbing		7,500	6.1
Control structures		7,000	5.7
Other		10,000	8.2
Total		121,980	

Since the USEPA database was published, there have been numerous additional constructed wetlands designed and built, especially in the range less than 50,000 gallons per day (gpd). The costs for these systems can be presented in two ways: as a function of $/day of detention time and as a function of $/gpd. Costs are presented this way because designs have different treatment objectives (e.g., BOD removal, or BOD and nitrogen removal), and systems with similar flows but different design objectives may have very different costs.

7.2 Operation and Maintenance Costs

Wetlands are almost invariably one part of a multipart treatment system. A few items in wetland systems require maintenance or energy. Determining actual operating costs from the database is difficult because the wetlands labor costs are lumped into the total system costs. However, an estimate of costs can be made by inspection of the design and recognizing that in many respects wetlands are very similar to wastewater stabilization lagoons from an O&M perspective. Operational costs can be divided into the following general categories:

- Operation—testing, water level adjustment
- Maintenance—weed control, flow distribution, and level adjustment sumps

The cost of testing influent and effluent, generally the largest single cost, depends on frequency, the number of water quality parameters, and the number of samples. Testing a sample for BOD, TSS, TKN, and nitrate and ammonia costs approximately $150.

Level adjustment usually requires little attention. Water levels should be checked periodically (monthly or weekly on small systems, and daily on systems >100,000 gpd) to ensure that there is some flow through the system and no surfacing has occurred in an SSF system. The level in SF wetlands must be visually inspected using a fixed gauge and the level adjustment checked.

Weeds should be controlled around the edges, and large weeds should be removed from the gravel bed in the early spring. Plant debris in SF wetlands can be ignored as long as it does not affect the flow; for example, plant debris after a severe storm may blow downstream and clog the collection piping or level adjusting structures. Regular inspection of the flow distribution and collection devices should be part of the operating requirements for the system. Flow splitters using weirs should be checked and cleaned periodically.

Some systems have incorporated annual harvest of wetlands plants. In the fall, prior to the plants becoming senescent, the plants are mowed and the litter removed to a composting operation. This operation removes stored nitrogen that would otherwise be released the following spring. Although there is a limited amount of information regarding this type of operation, the cost does not appear to be justified by the value of the harvested nitrogen or the minimal increase in nitrogen removal.

Actual reported costs for all operations support the notion that wetlands are very low-cost systems. The annual O&M costs for Denham Springs, Louisiana (3 mgd) were $29,550, including the costs of operating the aerated lagoon and chlorinator. Mesquite, Nevada (0.4 million gallons per day) has an operating budget of $10,000. This data provides an operating budget range of 2.6–6.8¢/1000 gpd.

7.3 Summary of Costs

Any energy-intensive wastewater treatment technology will be much more expensive to operate than constructed wetlands. Reed and Brown (1992) indicate that, in the wetlands they surveyed, the average cost for an SF wetland was $22,000/acre, while the average cost of a SSF wetland was $87,000/acre. The basic exchange is energy for land. As the area of a treatment system increases, energy and operating costs decline. As area decreases, energy must be added to the wastewater treatment process to accomplish what more expansive natural processes could have accomplished without assistance.

The cost of land is an obvious missing element in the comparisons in the next section, except for the Hanson's Lakes example. Since most wetlands have been built in rural areas where land costs are low or on land that is not suitable for building, land costs generally have little impact on the cost of constructed wetlands. However, if wetlands are considered for urban areas, then the cost/benefit analysis should include land costs and also the benefits that accrue for open space, habitat, and recreation.

Because of the simplicity of the technology, the low operational and construction costs, and the additional benefits that accrue, wetlands should be considered in the design of new systems and the upgrade of existing wastewater treatment systems.

7.4 Cost Comparisons with Other Technologies

SSF constructed wetlands have been used primarily for small community systems. As the database indicates, over half the systems are less than 100,000 gpd. The reasons for use as small community systems are primarily economic as the following case will demonstrate.

<u>Example 1—Hanson's Lakes, Nebraska</u>

The small development of Hanson's Lake, Nebraska has 235 homes located around two small lakes adjacent to the Platte River. The nearest sewer interceptor for the City of Omaha is 1.5 miles away. Design flow is 75,000 gpd. The following options were considered during planning:

- pump to the City of Omaha,
- mechanical package treatment system,
- constructed wetlands and sand filter, or
- wastewater stabilization lagoon and sand filter.

The City of Omaha has a wastewater treatment charge of $1.46/1000 gallons, which is typical for municipal systems without advanced waste treatment standards. In addition, the City of Omaha would require a $300,000 capital charge. This capital charge of approximately $1,300/home is now typical of the charges many municipalities are initiating as part of the sewer hookup fee. Other capital costs included the cost of a lift station and 1.5 miles of sewer line to the city interceptor.

The mechanical package treatment system proposed was a sequencing batch reactor (SBR). SBRs have an excellent operating history and can produce an excellent quality effluent; however, operating costs are significantly higher than those for constructed wetlands or the cost of treatment at the City of Omaha. This relationship is typical of small systems.

Both wastewater stabilization lagoons and wetlands have nominal operating expenses. There is no energy cost or equipment to maintain, and both systems can treat a certain amount of sludge. Although the least expensive to build and operate, wastewater stabilization lagoons would require 160 acres of land to provide a buffer for odors, and since land is not immediately adjacent, a small lift station would be required. The wetlands would not require a buffer; consequently, as Table 7-3 indicates, a wetland is the least cost option. The 20-year total is based on a 3% inflation rate for O&M and a 6% interest rate for the construction loan. Table 7-3 compares costs, including land, legal, and engineering, of the various technologies evaluated by the Hanson's Lake development.

Table 7-3. Cost Comparison of Treatment Systems over 20 Years

Option	Capital	O&M	20-Year Total Cost
City of Omaha	826,000	1,420,253	$2,720,779
Sequencing batch reactor	596,700	1,657,902	$2,683,889
Lagoon and sand filter	742,600	139,726	$1,416,984
Wetlands and sand filter	365,300	206,902	$835,012

The following example further illustrates the issues regarding costs.

Example 2—Golf Course Subdivision

120 homes, 60,000 gpd design flow with the following alternatives:

- SBR—$250,000 for construction, $2.50/1000 gallon operating cost
- Constructed wetlands and sand filter—$265,000 for construction, 10¢/1000 gallon operating cost

Although the constructed wetlands and sand filter cost slightly more to construct, the significantly lower O&M costs will make the constructed wetlands the more cost-effective choice. The difference in capital costs will be repaid in 104 days of operation.

Example 3—Mine Drainage Treatment, Dunka Mine, Babbitt, Minnesota

A total of $1.2 million was spent to construct five wetland systems to treat mine drainage. The design of these systems changed over time, and costs ranged from $18/m^2$ to $24–28/m^2$. A standard lime treatment plant was initially constructed to treat the drainage, at a cost around $1.3 million. This plant had an annual operating cost of $200,000. Maintenance costs for the wetland systems generally decreased as vegetation became mature, and by the fourth season the only maintenance required was inspections in the spring and fall, which cost less than $2,000, or less than 1% of the cost of the treatment plant. With an annual savings of $198,000, the costs to construct the wetland treatment systems will be recovered in 6–7 years.

Figure 7-1 shows the total cost distribution of 24 case studies collected while researching this document. Seventeen of the 24 case studies are full-scale.

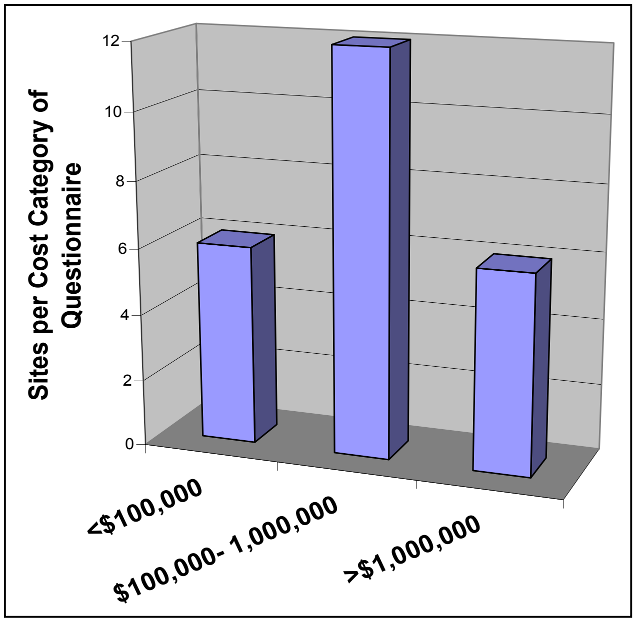


Figure 7-1. Case Study Cost Range

8.0 REGULATORY FRAMEWORK

Many local, state, and federal regulations, laws, and policies must be considered before initiating a constructed wetland project. As with many remediation or contaminant-control projects, regulators, the general public, and other stakeholders may need to be consulted during the application review and approval process. The ITRC *Phytotechnology Technical and Regulatory Guidance Document*, available online via "Guidance Documents" page on the ITRC Web site (http://www.itrcweb.org), provides a list of questions likely to be asked during the application and approval process. Most of these questions apply directly to constructed wetlands, especially where used to remediate contaminants.

Even though the treatment mechanisms are parallel to phytotechnology mechanisms, other pollution control regulations often oversee this application. Federally, these include the Clean Water Act Section 402 (National Pollutant Discharge Elimination System) and Section 404 (Wetland Fill Program), and for federal actions, the National Environmental Protection Act (NEPA). The Endangered Species Act (ESA) may apply if an endangered species is potentially found in the area where a proposed constructed wetland is to be sited. If a constructed wetland is used to treat a hazardous substance, that action may be regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); Resource Conservation and Recovery Act (RCRA); or state cleanup regulations. Table 8-1 summarizes these laws.

Table 8-1. Federal Laws Overseeing Resources Potentially Impacted by Constructed Wetlands

Federal law	Responsibility	Purpose
Clean Water Act (CWA)	USEPA administers Section 402 of the National Pollutant Discharge Elimination System for point and nonpoint sources of pollution. The U.S. Army Corps of Engineers is responsible for Section 404.	Management of, and construction in, natural or created wetlands
National Environmental Policy Act (NEPA)	Administered by the Council of Environmental Quality (CEQ)	NEPA requires federal agencies or anyone conducting an action on federal lands to consider the environmental impacts of that action.
Endangered Species Act (ESA)	Administered by the U.S. Fish and Wildlife Service	Protects all endangered or threatened species in and around a project site
Migratory Bird Treaty Act (1918)	Administered by the U.S. Fish and Wildlife Service	Protects the movement and reduces harm to migratory birds

It is important that planners consult local and state requirements since these may be more stringent than federal regulation. It is also beneficial to involve state and local regulators early in the design process to ensure compliance with the range of laws, regulations, and ordinances. Furthermore, since the general public views wetlands favorably, in certain instances it is beneficial to solicit public involvement to aid in acceptance of a constructed wetland project.

It should be noted that constructed wetlands should not be confused with created wetlands, which are established to mitigate impacts to natural wetlands from a construction project or to receive wetland credits in a wetland mitigation bank. Created, or “mitigation”, wetlands are under considerably more regulation and are generally not used for treatment. In the future, ITRC will produce a guidance addressing mitigation wetlands.

8.1 Clean Water Act

The Clean Water Act (CWA) regulates all water bodies legally considered “waters of the United States” (referred to here as “regulated waters”) for waste treatment, discharge into, and fill activities. A constructed wetland may require two unrelated CWA permits—NPDES and Wetland Fill.

8.1.2 CWA Section 404

The U.S. Army Corps of Engineers (USACE) and USEPA covers fill activities into wetlands. Natural wetlands, created wetlands, and natural wetlands used for treatment are all considered regulated waters. Any fill and most construction activities in these wetlands require a fill permit. Constructed wetlands built in upland areas are not normally considered “waters of the United States” (Hammer, 1992). However, USEPA is currently evaluating the concept of allowing some treatment wetlands to also act as mitigation wetlands. These would then be considered wetlands and subject to regulation under Section 404.

8.1.3 CWA Section 402

The NPDES program requires a permit for all discharges into regulated waters. Section 402 is administered by USEPA or delegated to the appropriate state agency. Federal NPDES permits apply only to surface water, but some states (e.g., New Jersey) have developed state programs to regulate discharges to groundwater

Most constructed wetlands are regulated as point source discharges under CWA Section 402. USEPA, or the delegated state, regulates these discharges through a permitting process. For example, a constructed wetland used as the final effluent polishing of a process wastewater that discharges to surface waters is required to obtain an NPDES permit. Another example includes stormwater runoff from an industrial site with a regulated standard industrial classification (SIC) code. The permitting authority incorporates established numerical effluent standards, developed on an industry-by-industry basis (technology-based). In this case, the owner/operator of the discharging facility would be responsible for permit compliance.

Point source discharges to the sanitary sewer system generally require a pretreatment permit from the local publicly owned treatment works (POTW) authority. The CWA requires the POTW to meet certain effluent standards on its own NPDES permits. In turn, the POTW issues pretreatment permits to users of its system to ensure their discharges meet numerical limits and will not cause the treatment works to violate its effluent standards. In addition, USEPA has established both general discharge requirements for industrial wastewater users and specific effluent limits from certain industrial categories.

Constructed wetlands functioning as pollution treatment devices for industrial stormwater or nonpoint source discharges and then discharging as point sources into regulated waters must be covered by an individual, general, or multisector NPDES permit. If the wetland system has dry weather discharge, then an individual permit is required, with attendant periodic monitoring to determine whether numerical effluent limits for particular pollutants are being met.

8.1.4 Construction in Wetland Areas

Ideally, constructed wetlands should not be sited in areas regulated under CWA Section 404, but some constructed wetlands may impact regulated waters. Any activity (e.g., maintenance or construction) that results in the discharge of dredge or fill material into regulated waters is covered under Section 404, and a permit must be obtained from USACE and/or appropriate state agencies unless the fill activity is deemed exempt. For example, constructing an outlet structure for a constructed wetland that protrudes into regulated waters will likely require a Section 404 permit. If a permit is required as a result of O&M activities, USACE will ask for concurrence from the following agencies before issuing the permit:
- U.S. Fish and Wildlife Service (USFWS)
- National Marine Fisheries Service (NMFS)
- State historical preservation office for cultural resources
- USEPA for water quality certification (CWA Section 401)

If it appears that coastal fisheries, historical or cultural resources, or water quality may be adversely affected, then the federal agency(s) or state agency responsible for the affected resource should be contacted.

8.2 National Environmental Policy Act

A constructed wetland built or permitted by a federal agency is subject to the National Environmental Policy Act process. Simply stated, NEPA directs the lead agency to consider the environmental and human health impacts associated with all “major” projects. If a proposed project has direct and localized impacts or it is unclear if the impacts will be “significant,” an environmental assessment (EA) is performed. If no “significant” impacts are identified by an EA, a finding of no significant impact (FONSI) is declared, and the NEPA process is complete. However, if the EA identifies the impacts as “significant,” an environmental impact statement (EIS) is required. Incorporating modifications and mitigating measures until the impacts are no longer “significant” can satisfy the EIS requirement, and a FONSI can be issued. The EIS process is lengthy, costly, and involves multiple agencies and public review. As of 1996, no constructed or created wetland had been subjected to the full EIS process (Kadlec and Knight,

1996). A project can fall under a categorical exclusion (e.g., water treatment works under approximately 250,000 gpd) and be exempt from the administrative procedures.

8.3 Endangered Species Act

If a constructed wetland were to be constructed in an area providing habitat for an endangered species, construction could be restricted under the Endangered Species Act or state equivalent. In addition, a constructed wetland can create habitat for endangered species, exposing the wildlife to an unhealthy environment. It is recommended that siting of the proposed constructed wetland not be attempted in such situations.

The ESA applies if endangered or threatened species are found in or around the site. Under the act, threatened or endangered species cannot be harmed or adversely affected by humans. If ESA-regulated species are suspected to be in or around a proposed site, field verification may be needed to see whether the species actually inhabits the area, and if so, care must be taken to avoid harm to it or its environment.

USFWS and NMFS administer the ESA. USFWS, which maintains a list of all threatened and endangered plants and animal species, can stop or postpone a CWA Section 404 permit on the grounds that the project has negative impacts to a listed species. However, a wetland project may enhance the habitat of a listed species and have positive impacts. USFWS should be involved in the project planning stage to determine whether a proposed project site may contain any listed species.

8.4 Other Federal Regulatory Authorities

Congress has passed several laws to protect cultural resources, including historical and archeological sites. Each law directs federal agencies, or private projects on federal lands, to protect historical, cultural, and archeological treasures. Table 8-2 presents the four major federal acts pertinent to federal activities (NAVFAC, 1997). Constructed wetland projects should address and comply with procedures, programs, and requirements associated with these laws.

8.5 Executive Orders

Federal executive orders may influence construction of a treatment wetland. For instance, Executive Order 11990, Protection of Wetlands (42 FR 26961, May 25, 1977) directs federal agencies to minimize degradation of wetlands and enhance and protect their natural and beneficial values. Executive Order 11990 directs USEPA when evaluating an NPDES permit application with wetland discharge to minimize the destruction, loss, or degradation of wetlands and to preserve and enhance the natural and beneficial values of wetlands. Executive Order 11988, Floodplain Management (42 FR 26951, May 25, 1977) requires federal agencies to avoid direct or indirect support of development within floodplain areas.

Table 8-2. Summary of Federal Historical, Cultural, and Archeological Legislation

Federal law	Purpose/goal	Federal agency requirements
National Historic Preservation Act (NHPA), 16 U.S.C. 470 et seq.	Prevention loss of irreplaceable historic properties	• Establish program to locate, inventory, nominate, and protect all properties, which appear to meet National Register criteria of significance. • Determine project effects on historical properties prior to undertaking project.
Archeological Resources Protection Act (ARPA), 16 U.S.C. 470 et seq.	Preservation and loss prevention of archeological resources	• Permit needed for authorized professional excavations or removal of archeological resources. • Survey all properties under control of agency by cultural resource professional to locate National Register resources.
American Indian Religious Freedom Act (AIRFA), 42 U.S.C. 1996	Consideration of issues of Indian religious value	• Consult traditional religious leaders and consider (but not necessarily defer to) Indian religious values. • Permit access to religious sites.
Native American Graves Protection and Repatriation Act (NAGPRA), 25 U.S.C. 3001–3013	Return of certain human remains and cultural items held by federal agency	Follow procedural requirements for returning NAGPRA-defined cultural items to American Indians, Native Hawaiians, and Native Alaskans, if requested.

8.6 State Variability

Constructed wetland project planning requires a thorough review and analysis of applicable state and local rules, regulations, and ordinances. State environmental regulatory programs may require additional permits or compliance with more stringent regulations. For example, the constructed wetland project listed below required three city permits and three state permits but only one federal permit.

Each state may have unique requirements based on climatic conditions and ideology. For example, constructed wetlands in the state of Arizona can have “no discharge” due to the high evapotranspiration rates found in most of the state. These wetland systems likely have some discharge to groundwater and are regulated under the state’s Aquifer Protection Permit Program. Since there are no surface water discharges, an NPDES permit is not required. Thus, because of their unique requirements and likely applicability to a constructed wetland project, state and local regulations should be considered early when planning a constructed wetland. Table 8-3 illustrates this point by comparing the permit requirements for a proposed constructed wetland in Renton, Washington.

Table 8-3. Comparison of Permit Requirements from City, State, and Local Jurisdictions

City of Renton	Washington State	Federal
• Shoreline Development Permit • Grade and Fill Permit • Environmental Review	• Shoreline Management Act • Hydraulic Project Approval • Water Quality Certification (CWA Section 401)	• Individual Fill Permit (CWA Section 404)

8.6.1 Municipal Wastewater Treatment

Taking Oklahoma as a specific state example, the applicability of constructed wetlands as a treatment alternative is dependent on discharge standards under the jurisdiction of the Department of Environmental Quality (ODEQ) and the receiving water body. The Oklahoma Water Resources Board (OWRB) sets water quality standards (WQS) for all "waters of the state." ODEQ is delegated the authority to regulate discharges into these waters under CWA Section 402. An Oklahoma Pollution Discharge Elimination System permit for point source discharge is required for constructed wetlands used for treatment purposes, and the permit contains the requirements necessary to ensure compliance with the WQS. For municipalities, the discharge limits require at least secondary treatment of wastewater. The actual permit effluent limits for a facility with a waste load allocation of "secondary treatment" can be determined by knowing the stream class (perennial or intermittent) and the current treatment process (mechanical plant or lagoon, etc.), then referring to the ODEQ regulations (Title 252, Chapter 605) entitled "Discharge Standards" for the limits. For discharges into a perennial stream from a constructed wetland treating municipal wastewater, the secondary treatment effluent limits would be 30 mg/L BOD_5, 30 mg/L TSS (on a monthly average basis), and pH 6.5–9.0.

Where multiple dischargers exist along a stream segment, stream studies are required to determine the appropriate waste load allocations to protect the designated beneficial use for that stream. These may be so restrictive that constructed wetlands would have a difficult time meeting the limits (e.g., when background concentrations within the wetland are greater than the permit requirements). Limits for fecal coliform bacteria and nutrients (nitrogen and phosphorous) may be required. Depending on the concentrations of the water to be treated, liners may be required by ODEQ regulations. ODEQ also requires a construction permit.

8.6.2 Stormwater Control

State and local regulatory agencies set specific requirements overseeing water quality and reducing peak flow rates from new urban development. Generally, water quality factors for basic treatment focus on reducing the average annual TSS loading by 80% after construction is completed and the development is permanently stabilized. The removal of 80% TSS is assumed to control, to a degree, heavy metals, phosphorus, and other pollutants. Certain states have gone a step further and identified enhanced treatment performance goals for dissolved metals, phosphorus, and total petroleum hydrocarbons. For example the state of Maryland has a requirement of 40% removal of total phosphorus from stormwater.

An NPDES permit establishes requirements for stormwater runoff from industrial activities. A permit imposes specific monitoring criteria and effluent limitations for pollutants in the

stormwater discharge. Feasibility of a constructed wetland is evaluated based on the NPDES permit criteria.

For quantity control, the focus by government agencies is typically on the infrequent storms such as the 2-, 10-, and 100-year storms. Regulations for new developments generally require that postdevelopment peak runoff rates from infrequent storms meet or are reduced from predevelopment peak runoff rates. A properly designed constructed wetland can generally meet the water quality and quantity requirements imposed by state and local stormwater management regulations.

Water quality design is usually based on treating the first 0.5–1.0 inch of runoff from impervious areas, typically referred to as the "first flush." However, it should be noted that the water quality design criteria could vary significantly state to state. For instance certain states will specify that runoff volumes and peak flow rates be treated for a specific design storm.

9.0 REGULATORY EVALUATION

If constructed wetlands are selected as a remedial alternative, design information must address regulatory and policy issues. This chapter summarizes regulatory and policy issues and concerns associated with the use of constructed wetlands and provide recommendations to address them.

Constructed wetlands are engineered structures designed to address and correct a variety of waste streams. When implementing constructed wetlands at a site, it is be important to inform regulators, stakeholders, and the public on how constructed wetlands work. The following questions are likely to be raised:

- What is the regulatory driver for cleanup (Voluntary Cleanup, CERCLA, RCRA, NPDES, etc.)?
- What is the contaminant of concern?
- What are discharge limits for the contaminant, and will these be attained?
- Will human health and ecological risks be adequately addressed?
- What will be the monitoring requirements for the site?
- What research has been conducted regarding the effectiveness of constructed wetlands?
- What will be the effect of genetically modified or nonnative plants if they are to be used at the site?
- What is the fate and transport of the contaminant in the wetland?
- How will contaminated substrate be disposed of?
- Will there be a contingency plan if the performance data indicate the system is not achieving the performance requirements within a specified time frame?
- Will a periodic review be conducted to re-evaluate the effectiveness of constructed wetlands at the site?
- What happens to the wetland when it is no longer needed?
- What provisions are necessary for winter operations?
- How long will the system last?
- What are the maintenance requirements?
- Will the contaminant of concern accumulate in plants to levels that are toxic to plants and/or animals?

9.1 Treatment Objectives

The key to successfully applying any technology is ensuring that the technology is applicable to the treatment objectives and site conditions. Constructed wetlands should include a mechanism for stabilizing, sequestering, reducing, degrading, metabolizing, or mineralizing contaminants. For inorganic contaminants, constructed wetland mechanisms that may be included in an application include filtration, settling precipitation, ion exchange, chelation, and bacterial degradation. For organic contaminants, applicable mechanisms include phytostabilization, rhizodegradation, phytodegradation, and phytovolatilization.

Recommendation
A constructed wetland application should include sufficient background information describing the treatment mechanisms of the treatment system. Applications could reference case studies, bench- or pilot-scale tests conducted specifically for the proposed application, or a literature review. Several case studies are provided in this document for each of the various constructed wetland applications (see Appendix A). These are active and ongoing projects the reader should consult to review their progress to date. An extensive bibliography is also provided.

9.2 Regulatory Evaluation and Approval

Each application of constructed wetlands is site-specific. Regulations (40 Code of Federal Regulations [CFR] 300.430) specify that a treatment remedy must be "protective of human health and environment, maintain protection over time, and minimize untreated waste." The view of the regulator on the applicability of constructed wetlands must be the same as for any other technology.

Recommendation
To obtain regulatory approval, sufficient data should be presented early in the process to avoid any uncertainty at the later stages of design. Using this data, system designers must demonstrate how constructed wetlands will decrease risk and meet all appropriate performance standards.

9.3 Permit and Ordinance Requirements

Constructed wetlands may require approvals and/or permits from one or more regulatory authorities (federal, state, and/or local) depending on the mechanisms involved and the applications being proposed. If surface water is being impacted, an NPDES permit may be required at the final point of discharge. City or county ordinances need to be consulted before a constructed wetland system design can be approved, specifically because many restrict the use and cultivation of plant species that may be considered invasive or noxious.

Recommendation
Always consult city, county, and state lists of plants classified as invasive or noxious. These can normally be obtained from the local Cooperative Extension Agent (see a national listing of Cooperative Extension Agencies at http://www.reeusda.gov/1700/statepartners/usa.htm)

9.4 Performance

Many factors affect the performance of constructed wetlands, including the composition, concentration, solubility, toxicity, and other chemical properties of contaminants. Winter operation presents difficulties not only because of the physical problems with ice buildup and flow problems, but also because the rates of chemical and biological reactions slow as the water temperature lowers. Monitoring variations in the performance of constructed wetlands in colder seasons is important to understand the seasonal performance and maintenance requirements of wetlands.

Recommendation
System designers must account for the seasonal variability of constructed wetlands and ensure that the system will meet treatment goals even during winter months.

9.5 Compliance versus Treatment

Almost all wetlands provide treatment of mine drainage, but they may not always provide consistent compliance. At some sites, for example at abandoned mine sites in remote locations, complete regulatory compliance may not be necessary to improve water quality and restore aquatic life to the impacted receiving waters.

Recommendation
In these specific cases the ITRC Wetlands Team recommends flexibility in treatment goals since complete compliance with water quality standards may not be achieved.

9.6 Time to Establish Wetlands

Constructed wetlands are limited by the plant growth rate, rooting depth, and length of the growing season. Because of these limitations, longer times may be required to achieve treatment goals than with other methods such as standard chemical treatment techniques. Constructed wetlands may take several years to complete, whereas traditional methods may only take weeks or months. However, if the projected risks over time are shown to be minimal through a suitable risk analysis, constructed wetlands may be more cost-effective than other alternatives. On the other hand, constructed wetlands may not be the remediation technique of choice for sites that pose acute or chronic risks to humans and other ecological receptors. Furthermore, risks may change seasonally, depending on the growth cycle of the vegetation.

Recommendation
In general, constructed wetlands are not recommended for short duration time-critical cleanups but are suitable for sites where time is less of an issue or wastewater management is a normal operational process. Regulators, community stakeholders, and site owners should mutually establish and understand a length of treatment time considered reasonable.

9.6.1 Achieving Treatment Goals

The treatment levels established for sites are based on protection of human health and the environment, regardless of the remediation technology used. To determine whether constructed wetlands can treat to the cleanup goals within the specified time frame, greenhouse tests or pilot studies should be conducted. These tests should directly test the proposed plant species with the contaminants of concern.

Recommendation
If sufficient background information is available in the literature, the system designer should use that literature review to defend the expected performance of an adequately designed system. This review should include a list of the contaminants of concern, the plant species and or mechanisms shown to treat those contaminants, the contaminant concentrations examined, and the time frame

to reach the specified endpoints. Finally, from that list of results, the system designer should recommend which specific plant species should be used in the constructed wetland system.

Recommendation
Appropriate parties should document the expected future use of the site and whether it is compatible with sustaining the wetland or removing all traces of the wetland.

9.7 Contaminant Fate and Transport

Since constructed wetlands can be considered treatment systems that use natural systems to stabilize, sequester, accumulate, degrade, metabolize, or mineralize contaminants, ecosystems that develop as a result of a constructed wetland project are subject to fate and transport mechanisms. These fate and transport mechanisms could be a concern to regulators, stakeholders, and the public and must be evaluated as part of the treatability and design processes. The mechanisms must be understood before a constructed wetland system can be implemented. Issues with fate and transport mechanisms include whether the contaminant being treated by the constructed wetland is toxic to plants, whether the plants grown at the site pose additional risks for further ecological exposure or food chain accumulations, and whether the contaminant is transferred into the air or transformed into a more toxic form. At the heart of these issues is whether the contaminants or contaminant byproducts are bioavailable to ecological receptors that frequent the constructed wetland or can be converted into mobile forms that can impact groundwater. However, it must be noted that these very fate and transport mechanisms—which may become an issue—are the basis for the ability of the constructed wetlands to treat/remove pollutants from the influent.

The environmental fate of contaminants entering a wetland includes elimination, transformation, immobilization, incorporation, and system exodus. The concentration of some pollutants may be reduced by more than one fate mechanism. Upon entering the wetland, transport mechanisms include diffusion, gravity settling, hydraulic travel through the wetland, vegetative translocation, and, in some cases, transfer to groundwater flows. In the case of elements such as phosphorus or trace metals, long-term storage in the wetland detritus and soil is responsible for most of the removal. Furthermore, each pollutant has its own chemical properties that result in variable affinities to each of the various endpoints.

Wetlands sequentially degrade and eliminate most organic pollutants, other organic matter, and nutrients primarily through biological activity. Metals removal is often a biophysical consortium of processes. An aerobic microbial process, which metabolizes compounds such as benzene or other organic matter into simpler products of carbon dioxide and water, is an elimination fate process.

Some chemicals will be transformed into less noxious or less hazardous substances, while others will be translocated, immobilized, or concentrated. The majority of compound transformations and immobilization occur as a result of biological activity within wetland soils, sediment, and detritus layers. The layers bind organic chemicals, inorganic compounds, and metals. At the same time, bound biodegradable compounds are either fully degraded or further transformed into less toxic compounds. Partially treated pollutants, transformed contaminants, and volatile

compounds can exit a wetland through atmospheric diffusion, groundwater leakage, and the system outlet.

Metals and nondegradable compounds tend to accumulate in wetland components. Most of the accumulation occurs in the soil and sediment layers. These layers bind contaminants well and become environmental endpoints. Most of the metals are removed from water by the soil layers. Metal removal rates can vary greatly depending upon the influent concentrations and hydraulic loading rates. However, in wetland systems under anaerobic sediment conditions, mercuric ions are biomethylated by a series of anaerobic microorganisms to methyl (mono- and dimethyl) mercury. Methylated mercury is a serious problem in aquatic ecosystems, being readily biomagnified in the food chain and highly toxic. Thus, when the effluent to be treated contains mercury, it is likely that some of the mercury will be transformed in wetland systems to methylated forms, generating additional environmental problems.

Recommendation
In general, elevated levels of mercury and mercury compounds should be removed from contaminated waters before being discharged to wetland treatment systems or the systems should be closely monitored to ensure that methyl mercury is within acceptable limits.

When disposal of a wetland substrate is required because of operation/maintenance requirements, disposal is driven by the contaminants that have become sequestered within the soil or plants. Characterization of the organic and inorganic constituents that may be found in the soil or plants must be determined to ascertain the appropriate disposal activity. For RCRA-listed metals, the substrate would pass specific leaching tests to determine proper disposal requirements. For many metals, however, the most stable location for permanent disposition is in the wetland environment. In particular, reduction in wetlands provides a stable environment for those metals removed in anaerobic wetlands.

High concentrations of contaminants may inhibit plant growth and eliminate constructed wetlands as treatment options. The system designer must present evidence that constructed wetlands will work at contaminant concentrations and potential accumulation levels at the site. Plant species already growing at the site should be compared to plants documented in literature as effective.

Recommendation
If existing species cannot be found in the literature, greenhouse toxicity tests or bench-scale pilot tests should be conducted. If the tests show existing plants are not tolerant of contaminant levels, a species found in the literature should be considered. As always, a preference is held for native species and equal attention should be given to avoiding introduction of noxious or invasive plant species.

9.8 Concerns with Human Health and Ecological Exposure

Constructed wetlands are designed to remove constituents of concern from the influent, enabling the processed water to be safely released downstream into the environment. Upon regulatory approval, these constructed wetlands can be placed in positions in the landscape, required to

fulfill certain functions of natural wetlands, and included in a net benefit analysis. However, as a filtering device, constructed wetlands may retain metals and organic chemicals that can eventually reach concentrations harmful to either ecological receptors or human health. SF wetlands are more susceptible to these concerns because of their open environment and easy exposure to ecological receptors (Reed and Brown, 1992).

9.8.1 Human Health Risk Assessment

Constructed wetlands can and have been successfully used for aesthetic and cultural purposes as environmental interpretative centers. Depending on the use of the constructed wetlands, either receiving primary effluent or receiving secondary effluent can mean a major difference in the potential exposure mechanisms and possible human health concerns (USEPA, 2000).

Recommendation
USEPA (2000) recommends that humans not be allowed in contact with wetlands being used to treat municipal wastewater to meet secondary treatment standards.

Property management such as fencing and signage should be used to preclude exposure of humans to direct contact with effluent.

Human health risks and toxicology should be addressed at some other point in the design/permitting process. If people will not be visiting the site or consuming anything that lives in the wetland, it is unlikely any exposure pathway exists. Without exposure, there is no risk. However, if there are exposure pathways, then a human health risk analysis is warranted.

9.8.2 Ecological Risk Assessment

In constructed wetlands, metals such as arsenic, cadmium, chromium, nickel, and zinc—as well as organic constituents—may collect in soils, sediments, and plants. A prime example is the incidences of plant community changes, loss of species, fish die-offs, and bird kills that have occurred from selenium exposure at the Kesterson National Wildlife Refuge in California (Kadlec and Knight, 1996; Ohlendorf, 1989), although it is not a constructed wetland. As previously discussed, however, several studies have shown that for many of the metals associated with mine drainage, over 90% of their removal is associated with the substrate and only a very small amount becomes part of the plant (Eger et al., 1994; Wildeman, Brodie, and Gusek, 1993). Kadlec and Knight (1996) also note that there is no record of ecological impacts to fish or wildlife species associated with treatment wetlands designed to address municipal wastewater or stormwater.

The potential for food chain impacts to higher trophic-level organisms, either directly through use of constructed wetlands or indirectly through use of prey from constructed wetlands, is somewhat limited. Many metals (arsenic, cadmium, chromium, nickel, and zinc) do not tend to bioaccumulate from trophic level to trophic level, while metals that have affinity for lipids such as some forms of mercury (see Section 9.7 for mercury discussion) will biomagnify up the food chain (Kadlec and Knight, 1996). Chlorinated compounds such as organochlorine pesticides will

also biomagnify up the food chain. Many nonchlorinated organic compounds, both volatile and nonvolatile, will degrade in the wetland environment to a nontoxic form.

In the event that concerns are raised over the level of a particular constituent in constructed wetlands or as a means of assessing the need for maintenance or remedial activities within a constructed wetland, it may be necessary to consider the completion of an ecological risk assessment for that site. An ecological risk assessment is an iterative process for evaluating the likelihood that adverse impacts may occur or are occurring as a result of exposure to one or more stressors, in this case metals contamination. Ecological impacts may occur if the stressor has the inherent ability to cause one or more adverse effects, and the stressor co-occurs with or contacts ecological components that include diverse organisms within a population or community. The ecological communities that will potentially be affected include terrestrial ecosystems exposed to contaminated soils, and aquatic and wetland ecosystems exposed to contaminated surface water and sediments. The ecological risk assessment process is designed to help identify environmental problems, establish priorities for resolving those problems, and provide a scientific basis for possible actions.

Ecological risk assessments most commonly conform to the framework described in USEPA's *Framework for Ecological Risk Assessment* (EPA/630/R-92/001) and *Guidelines for Ecological Risk Assessments* (EPA/630/R-95/002F), which divide ecological risk assessments into three stages: problem formulation, analysis, and risk characterization. More detailed guidance on conducting ecological risk assessments is provided in *Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments* (EPA 540-R-97-006). This guidance expands the three-step framework into a multistep process by which a greater level of ecological scrutiny is placed, as needed, at each of the steps. However, following the more general guidelines is usually more appropriate unless the site has been identified as required to do so by a regulatory program

Recommendation
Designers must consider the potential ecological risk associated with each wetland project. However, there is no clear and consistent legal requirement to do so. Legal drivers vary from state to state and county to county, but some regulators will require an ecological risk assessment to be conducted as part of an EA or other permit requirement. It is always preferred that potential ecological risks be evaluated before installation of the constructed wetland, rather than after the effects have already occurred. Doing so makes it easier to incorporate changes into the design to protect the ecosystem.

9.8 Advantages, Limitations, and Stakeholder Concerns

All treatment and remediation technologies have their own advantages and disadvantages. During the process of collecting information and having discussions during the compilation of this document, the team wanted to highlight the following advantages and limitations. We do want to emphasize that problems with wetlands are not always due to a limitation of the technology but rather our inability to consider all possible variables that will be encountered during the treatment process. Treatment efficiency is a function of that ability. Likewise, the advantages do not present themselves unless proper design accounts for these positive benefits.

9.8.1 Advantages

- low-maintenance, passive, in situ, solar-driven system
- potentially applicable in remote locations without utility access
- decreased air and water emissions as well as secondary wastes
- control of soil erosion, surface water runoff, infiltration, and fugitive dust emissions
- capability to remediate sites with multiple or mixed contaminants
- habitat creation or restoration provides land reclamation upon completion
- favorable public perception, increased aesthetics, and lower noise than mechanical systems
- increasing regulatory acceptance and standardization
- carbon dioxide and greenhouse gas sequestration

9.8.2 Limitations

- Appropriate land must be available for wetlands construction.
- Constructed wetlands can be relatively slow in comparison to other treatment technologies.
- Constructed wetlands are dependent on local climatic conditions and may have reduced efficiencies during colder seasons.
- Constructed wetlands may become mosquito breeding grounds; however, this problem is preventable through proper consideration during design.
- Disagreeable odors associated with natural biological functions could arise due to anaerobic conditions. Proper design and control of organic loading rates reduces the potential for problem odors.
- Constructed wetlands may become a more permanent feature of the ecosystem, and long-term maintenance may be required.
- Contaminant accumulation must be monitored to maintain ecological health of the system.

In addition, through USEPA's Environmental Technology Initiative, a work group referred to as the Treatment Wetland Policy and Permitting Team issued a report (USEPA, 1997) identifying 13 issues pertinent to constructed treatment wetlands. Among the topics addressed in the report are water quality and biological criteria; siting relative to "waters of the United States;" design, construction, and operation and maintenance; and whether treatment wetlands should be used as mitigation wetlands. The ITRC Wetlands Team encourages the reader to refer to this document.

10.0 GLOSSARY

absorption—the movement of a dissolved chemical across a permeable or semipermeable membrane.

adsorption—the process by which a gas, liquid, or dissolved chemical adheres to the surface of a solid.

adventitious roots—roots that grow on other parts of the plant body, most often as a result of increased moisture and lack of a stable substrate; most often develop on the stem and serve to augment the normal root function of anchorage.

aeration—the addition of air to water, usually for the purpose of providing higher oxygen levels for chemical and microbial treatment processes.

ammonification—breakdown of organic nitrogen by decomposer organisms to ammonia.

anaerobic—lacking in free oxygen.

anion—a negatively charged ion.

anoxic—completely lacking in both free and chemically bound oxygen.

aspect ratio—ratio of wetland cell length to cell width.

benthic—the bottom sediments of wetland and aquatic ecosystems.

bioassays—laboratory analyses that use living organisms to test the toxicity of water.

biochemical oxygen demand (BOD)—amount of oxygen in water consumed by a waste through bacterial degradation.

BOD_5—the oxygen demand exerted over a five-day period.

brackish water—pertaining to water that contains a salt content greater than 0.5%.

bog—a wetland community that accumulates peat and has no significant inflows or outflows.

bulk density—a measurement of the mass of soil occupying a given volume.

buttress swelling—enlarged base of trees found in marsh settings; often occurs as a result of reduced stability in the substrate and the need for increased oxygen exchange.

caliche—a crust of calcium carbonate that forms on stony soils in arid regions.

cation—a positively charged ion.

cation exchange capacity—the ability of a soil to bind positively charged ions.

chemical oxygen demand (COD)—amount of a strong chemical oxidant that is reduced by a waste, the results of which are expressed in terms of the equivalent amount of oxygen.

denitrification—the process by which nitrogen gas is formed by the anaerobic microbial reduction of oxidized nitrate nitrogen.

detritus—dead plant material that is in the process of microbial decomposition.

diffusion—the movement of a substance through a gas or liquid from an area of high concentration to an area of low concentration.

dispersion—scattering and mixing within a water or gas volume.

diurnal—occurring in daylight.

dystrophic—lakes that receive large amounts of organic matter from the surrounding watershed.

effluent—a liquid or gas that flows out of a process or treatment system.

Eh—a measure of the reduction-oxidation (redox) potential of a soil based on a hydrogen scale.

epilimnion—in thermal stratification regimes in a lake, the freely circulating surface water with a small temperature gradient.

estuarine—wetlands consisting of deepwater tidal flats and adjacent tidal wetlands that are usually mostly enclosed by land but having at least sporadic access to the open ocean. The water associated with these wetlands is at least occasionally diluted by freshwater and generally extends from a point upstream where the salinity level is 0.5% to the seaward limit of wetland emergents.

emergent—those plant species in which at least a portion of the foliage and all of the reproductive structures extend above the surface of any standing water.

eutrophic—water quality conditions characterized by an abundance of nutrients, especially nitrogen and phosphorous, which stimulate a heavy growth of algae; water is very turbid and oxygen may be depleted in deeper areas.

evapotranspiration—a measure of the total amount of water lost by transpiration and evaporation from a given area.

fen—an emergent wetland community that accumulates peat and receives some drainage from surrounding soil.

free water surface (FWS)—another name for surface flow wetlands.

Habitat Evaluation Procedure (HEP)—a procedure developed by USFWS to evaluate the suitability of an area to provide habitat for wildlife.

hydraulic loading rate (HLR)—the volume of water loading to a constructed wetland measured in units of volume per area over time.

hydraulic residence time (HRT)—the average time that a given volume of water occupies a given space in the constructed wetland.

hydrophytic—type of plant adapted to living in saturated soil conditions.

hydric—water loving.

hypolimnion—in thermal stratification regimes in a lake, the deep cold layer of water.

influent—water, wastewater, or other liquid that flows into a water body or treatment unit.

knees—root structures that stick out of the surrounding substrate; found in bald cypress (*Taxodium distichum*) trees; thought to serve in oxygen support to the root system.

lacustrine—wetlands that include deepwater habitats found in topographic depressions or dammed river channels, which lack trees, shrubs, emergents, mosses, or lichen and exceed 20 acres in size.

leachate—liquid that has percolated through permeable solid waste and has extracted soluble materials from it.

lentic—standing freshwater aquatic habitats.

limnetic—the aquatic of a lake characterized by open water, the depth of which is determined by light penetration.

littoral—shallow water aquatic of a lake in which light penetrates to the bottom.

lenticels (expanded)—a corky spot or line in woody plants that helps in oxygen and water transfer. In some plants found in very moist environments, the lenticels have become enlarged.

lotic—moving freshwater aquatic habitats.

marsh—a wetland community dominated by herbaceous plants.

mass loading—the total amount of a constituent entering a system on a mass or mass per area basis.

mesotrophic—water quality characterized by an intermediate amount of plant growth nutrients.

metalimnion—in thermal stratification regimes in a lake, the area characterized by a steep and rapid drop in temperature.

nitrification—in the nitrogen cycle, the biological transformation (oxidation) of ammonia nitrogen to nitrite and nitrate forms.

nitrogen fixation—the conversion of nitrogen gas to ammonia or nitrate, generally through microbial processes.

oligotrophic—water quality conditions characterized by high levels of oxygen, low levels of nutrients, nitrogen may be high, and phosphorous may be highly limiting.

oxidation—a chemical reaction in which oxygen is added to a substance; also any reaction involving the loss of electrons from an atom.

oxygen sag—the decrease in dissolved oxygen measured downstream of point source in a flowing water system.

palustrine—depressional; a classification of wetland community that includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, and emergent mosses or lichens.

priphyton—community of organisms that are attached to or move upon a submerged substrate but do not penetrate it.

perennial—persisting for more than one year.

photic—the aquatic of a water body that is penetrated by sunlight.

precipitation—chemical process by which a substance, usually a metal, is changed to a state heavier than water and forced to drop out of the water column.

pretreatment—the initial treatment of wastewater to remove substances that might be harmful to downstream treatment processes.

primary production—the accumulation of energy by plants.

primary treatment—the first step in wastewater treatment, which usually involves screening and sedimentation of particulate solids.

profundal—the deep aquatic of a water body below the depth of light penetration.

redox potential (oxidation-reduction potential)—a measure of the electron availability in a solution.

reduction—a chemical reaction in which oxygen is given up, hydrogen is gained, or an electron is gained.

respiration—the intake of oxygen and the release of carbon dioxide as a result of metabolism.

rhizosphere—the chemical sphere of influence of plant roots growing in flooded soils.

riverine—a classification of wetland community found adjacent to a river or stream.

secondary production—the production of biomass by consumer organisms by feeding on primary producers or lower trophic-level consumers.

secondary treatment—refers to wastewater treatment beyond initial sedimentation and typically includes biological reduction in the concentrations of particulate and dissolved concentrations of oxygen-demanding pollutants.

sediment—mineral and organic particulate material that settles from suspension in a liquid.

seed bank—the accumulation of viable plant seeds occurring in soils and available for germination under favorable environmental conditions.

surface flow (SF)—a category of treatment wetlands designed to have free water above the ground surface.

subsurface flow (SSF)—a category of treatment wetlands designed to have the water surface below ground surface and having flow through a porous media.

sludge—the accumulated solids separated from liquids during a treatment process.

stabilization pond—a type of treatment pond in which biological oxidation of organic matte results by natural or artificially enhanced transfer of oxygen from the atmosphere to the water.

stage-area curve—the relationship between water depth and the surface area of a wetland or lake.

stage-discharge curve—the relationship between water depth and outflow from a body of water.

submerged plants—aquatic vascular plants that grow below the water surface for all or the majority of their life cycles.

substrate—medium on which an organism can grow.

succession—changes in plant and animal populations over time that occur in response to disturbances or as a result of natural processes.

swamp—a wetland community dominated by woody plants.

thermocline—in thermal stratification regimes in a lake, the point within the metalimnion at which the temperature drop is the most rapid.

transpiration—the passage of water vapor through pores in a plant.

vegetated submerged bed (VSB)—another name for a subsurface flow wetlands.

wetlands—As defined by the Clean Water Act, "those areas that are inundated or saturated by surface water or groundwater at a frequency or duration sufficient to support, and that under normal circumstances does support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas."

Wetland Evaluation Technique (WET)—a methodology revised by the U.S. Army Corps of Engineers to evaluate the functional qualities of a wetland.

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Other Available Resources

The following publications from the U.S. Department of Agriculture Natural Resources Conservation Service (formerly the Soil Conservation Service) are recommended for further information about construction activities:

Engineering Manual for Conservation Practices, 1989, Chap. 11, "Ponds and Reservoirs."

Landscape Design: Ponds, 1988, Landscape Architecture Note 2.

National Food Security Act Manual, 1988, Title 180-V-NFSAM.

Ponds: Planning, Design, and Construction, 1982, Agricultural Handbook No. 590.

Water Quality Field Guide, 1983, SCS-TP-160.

Internet Resources

http://www.bmpdatabase.org/ (full-scale examples)

http://www.ci.knoxville.tn.us/engineering/bmp_manual/default.asp

http://www.dot.ca.gov/hq/env/stormwater/index.htm

http://www.ecy.wa.gov/programs/wq/stormwater/index.html

http://www.frtr.gov/matrix2/section4/4_48.html

http://www.state.co.us/oemc/programs/wetlands.htm

http://www.state.ma.us/dep/brp/stormwtr/stormpub.htm

http://www.state.nj.us/dep/dwq/stormw.htm

http://www.njstormwater.org

APPENDIX A

Constructed Treatment Wetlands Case Studies, Compiled August 2002

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Response No. 1	Date 6/21/2002
Question	**Answer**
Name	Arthur Stewart
Telephone	(865) 574-7835
E-mail	stewartaj@ornl.gov
Site Name	Bear Creek Valley demo wetlands
Site Location	West of Y-12 National Security Complex, Oak Ridge, Tennessee
Size of Drainage Area	<1
Constituents of Concern	U (generally <1 mg/L), NO_3 (~35 mg/L as N)
Principal Investigator Name	same as above
Project Design and Application	Efficacy test; ability of constructed wetlands to reduce the level of uranium and nitrate from contaminated groundwater, which surfaced as a tributary to Bear Creek.
Flow Through System	<1
Constituents after Treatment	When wetland cells were "fed" corn liquor as a C supplement, removal efficiency of N was about 60%. U removal was ~50%, with or without corn-liquor augmentation.
Flow Through System Units	~1 gallon per min
Treatment Goals	DOE Environmental Restoration (ER) program objectives were to test efficacy (focus on U removal)—No clear technology demo "pass or fail" criteria were invoked.
Technologies–Other	Replicate wetland cells, demo-scale; cells were ~6 feet long, 2 feet wide, and contained pea gravel to a depth of ~40 cm. Well vegetated with 5–6 species planted, plus volunteers; solar-powered (battery back-up) peristaltic pump used to feed the cells. Gravity-feed used to dispense corn liquor, starting about halfway through the several-month-long study.
Duration of Treatment	~4 months
Project Scale	Demo
Issues Encountered	No regulators were involved; the project suffered from DOE ER overbearance and insufficient funding. More importantly, there was never a clear

	understanding about “if it works, will we actually scale up to use it?”
Project Cost to Date	$100,000 or less
Additional Info	Despite the very small-scale nature of the demo, it yielded clear evidence for N and U removal. The key to this success were systematic measurements of U and N concentrations in water entering and exiting each wetland cell–and this is where most of the expense was incurred, as well. The hardware (solar panels, batteries, cells themselves, pea gravel, plants, etc.) all performed well with minimal maintenance.

Response No. 2	Date 6/24/2002
Question	**Answer**
Name	D. M. Griffin, Jr.
Telephone	(318) 257-2356
E-mail	dmg@coes.latech.edu
Site Name	Grand Prairie, Louisiana
Site Location	Interstate 49 Rest Area, 18 miles north of Opelousas, La.
Constituents of Concern	Influent BOD, 500–3000 mg/L
Regulatory Contact Name	Robert Crawford, Louisiana DEQ
Plant Hardiness	Deep South, no plants used here.
Project Design and Application	Septic tank/rock filter system used to treat high-strength wastewater.
Constituents after Treatment	Long-term average BOD 19 mg/L
Flow Through System Units	6500 gpd
Treatment Goals	Long-term average BOD 45 mg/L
Technologies–Municipal Waste Treatment	Septic tank/rock filter system
Duration of Treatment	Complete operational data since November 1996
Project Scale	Full scale
Issues Encountered	No complete information
Additional Info	Very probably we have the largest and highest quality database.

Response No. 3	Date 6/24/2002
Question	**Answer**
Name	Edward R. Bates
Telephone	(513) 569-7774
E-mail	bates.edward@epa.gov
Site Name	Multiple sites
Site Location	Multiple
Principal Investigator Name	Various
Regulatory Contact Name	Edward R Bates and others
Technologies–Mine Drainage	Bioreactors (wetlands)
Project Scale	Field pilot
Project Cost to Date	$100,001 > $1,000,000
Additional Info	There have been several projects, all different. All used bioreactors to treat mineral mine drainage. Designs varied considerably. Three more are currently under design for construction this summer. People often refer to them as treatment wetlands; however, not all involve plants larger than microbes.

Response No. 4	Date 6/24/2002
Question	**Answer**
Name	Al Sever
Telephone	(570) 368-8337
E-mail	fsever@state.pa.us
Site Name	Julian Woods
Site Location	Huston Township, Pennsylvania
Size of Drainage Area	5 > 10
Constituents of Concern	Typical sewage—200 mg/L BOD, 200 mg/L TSS
Project Design and Application	Treats domestic wastewater from ~15 homes
Flow Through System	>1000
Constituents after Treatment	30 mg/L BOD, 30 mg/L TSS, 0.0 fecal coliform
Flow Through System Units	gpd
Treatment Goals	Secondary treatment
Technologies–Municipal Waste Treatment	Wetland for secondary treatment
Duration of Treatment	10 years
Project Scale	Full scale
Project Cost to Date	$100,001 > $1,000,000

Response No. 5	Date 6/24/2002
Question	**Answer**
Name	H. J. Thung
Telephone	(405) 702-8100
E-mail	Hj.Thung@deq.state.ok.us
Site Name	Dept. of Environmental Quality
Site Location	Oklahoma City, Oklahoma
Size of Drainage Area	10 > 100
Project Design and Application	Vegetated subsurface wetland to treat lagoon effluent generated at the Town of Binger, Maysville, and Colbert wastewater treatment facility. Design criteria: 24-hour detention time, 24 inches of filter media; 4 to 1 length to width ratio; vegetation: bull rushes or cattails
Flow Through System	<1
Constituents after Treatment	BOD > 30 mg/L, TSS > 30 mg/L; septic conditions; odor problem
Flow Through System Units	Million gallons per day
Technologies–Municipal Waste Treatment	Vegetated subsurface wetland system
Duration of Treatment	02/1991-02/1992
Project Scale	Full scale
Issues Encountered	The three systems failed within a year of operation. USEPA funded the projects under the Construction Grants Program, which provided 10% additional funding for an innovative or alternative technology. Subsurface wetland was then considered innovative technology. As the failure was not due to design deficiencies or third-party fault, under 40 CFR Part 35, federal funds could provide 100% replacement cost. The three municipalities received full funding to replace the failed vegetative subsurface system with a conventional total retention lagoon system.
Project Cost to Date	$100,001 > $1,000,000
Additional Info	Five vegetated subsurface wetland systems were constructed in Oklahoma in the early 90s. Four were replaced by total retention lagoon system within three years. One is still in operation, but it has not been working as designed.

Response No. 6	Date 6/24/2002
Question	**Answer**
Name	Robert W. Nairn
Telephone	(405) 325-3354
E-mail	nairn@ou.edu
Site Name	Gowen Wetlands Demonstration Project
Site Location	Gowen, Oklahoma
Previous Site Use	Underground and surface coal mining reclaimed for agricultural use
Size of Drainage Area	<1
Constituents of Concern	Mean ± standard error
Regulatory Contact Name	Jim Leach
Regulatory Contact Telephone	(405) 810-1039
Plant Hardiness	Not applicable
Project Design and Application	Vertical-flow wetlands and surface-flow ponds for removal of acidity and Fe loads from existing abandoned underground mine discharge
Flow Through System	10 > 100
Constituents after Treatment	Mean ± standard error
Flow Through System Units	Liters/minute
Treatment Goals	Demonstrate effective mine drainage treatment wetlands technology in Oklahoma
Technologies–Mine Drainage	Vertical flow wetlands (aka SAPS or RAPS)
Duration of Treatment	September 1998–September 2000
Project Scale	Field pilot
Issues Encountered	No
Project Cost to Date	$100,000 or less
Additional Info	This project was funded as an USEPA NPS Section 319 demonstration. A change in mine hydrology did not allow further study after September 2000. The wetlands were dozed in during the summer 2001 as part of a landowner agreement.

Response No. 7	Date 6/25/2002
Question	**Answer**
Name	Martin Maner, P.E.
Telephone	(501) 682-0542
E-mail	maner@adeq.state.ar.us
Site Name	Various
Site Location	Various municipalities in Arkansas
Size of Drainage Area	5 > 10
Constituents of Concern	BOD 200 mg/L
Regulatory Contact Name	Same as above
Plant Hardiness	Arkansas
Project Design and Application	Subsurface rock-reed filters for treatment of municipal sewage, typically from a single-cell facultative lagoon
Flow Through System	<1
Constituents after Treatment	BOD 15 to 25 mg/L
Flow Through System Units	mgd
Treatment Goals	Original goals were to meet NPDES permit values for BOD (usually about 10 mg/L) and ammonia (usually about 5 mg/L). The systems failed miserably at meeting the ammonia limits because the rock reed beds are anaerobic.
Technologies–Municipal Waste Treatment	Subsurface rock-reed filter treating single-cell facultative lagoon municipal waste
Duration of Treatment	2+ years
Project Scale	Full scale
Issues Encountered	Yes, these facilities typically did and do not meet their ammonia limits.
Project Cost to Date	$100,001 > $1,000,000

Response No. 8	Date 6/25/2002 10/15/02
Question	**Answer**
Name	John Pries, CH^2MHill-Canada
Telephone	(519) 579-3501, x228
E-mail	jpries@ch2m.com
Site Name	Brighton
Site Location	Brighton, Ontario, Canada
Previous Site Use	Cornfield
Size of Drainage Area	10 > 100
Constituents of Concern	Total ammonia, inflow 3–16 mg/L; other conventional constituents exist; however, ammonium is the driver.
Principal Investigator Name	Same
Principal Investigator Telephone	Same
Project Design and Application	Municipal wastewater polishing—postlagoon treatment
Flow Through System	>1000
Constituents after Treatment	0 to 13 mg/L
Flow Through System Units	m^3/d
Treatment Goals	10 mg/L summer, 15 mg/L winter
Technologies–Municipal Waste Treatment	Surface flow (free water surface) wetland for aeration followed by facultative lagoon effluent
Duration of Treatment	3 years
Project Scale	Full scale
Issues Encountered	Regulatory issue was related to unfamiliarity with the technology and uncertainty that objectives could be met. Therefore, the certificate of approval was provided for a five-year monitoring period with discharge objectives. After the five-year period, the wetland will have discharge limits based on performance. The Ontario Ministry of Environment established treatment limits at the discharge point of the lagoon system and performance targets at the discharge point of the wetland. After five years of operation, the point of compliance (monitoring the discharge limits) will be at the discharge point of the wetland system. Winter operation and water

	temperature is normally 1–2°C (33.8–35.6°F). In the summer, it ranges 25–30°C (77–86° F). Denitrification slows dramatically in the winter to 1.0–2.0 mg/L reduction of the ammonium, but it never completely stops. Weekly monitoring shows this as a transitional microbial rate from high to low temperatures.
Project Cost to Date	$100,001 > $1,000,000 $100K for engineering

Response No. 9	Date 6/25/2002, revised 10/15/02
Question	**Answer**
Name	William Ellett
Telephone	(520) 628-6714
E-mail	wje@ev.state.az.us
Site Name	Apache Powder CERCLA Site, Cochise County
Site Location	Benson, Arizona
Previous Site Use	Explosives and nitrate-based fertilizer manufacturing
Size of Drainage Area	>100
Constituents of Concern	Nitrate–N, mean ~100 mg/L, range ~40–150 mg/L
Principal Investigator Name	Leo Leonhart, Hargis + Associates, Inc.
Principal Investigator Telephone	(520) 881-7300
Principal Investigator E-mail	lleonhart@hargis.com www.hargis.com & www.apachenitro.com Design assisted by Dr. Robert Gearheart Humboldt State, (707) 826-3135
Regulatory Contact Name	Andria Benner, USEPA
Regulatory Contact Telephone	(415) 972-3189
Regulatory Contact E-mail	benner.andria@epa.gov
Plant Hardiness	Desert
Project Design and Application	Remediation of nitrate: N-contaminated groundwater to below 10 mg/L using cattails to develop plant detritus to create an anaerobic wetland.
Flow Through System	100 > 1000 currently, 30 gpm with molasses additive, target 100–150 gpm
Constituents before Treatment (Ave.)	Influent to wetlands @100–150 mg/L
Constituents after Treatment	Less than 10 mg/L when the system is fully operational
Flow Through System Units	Gallons per minute
Treatment Goals	Drinking water MCLs
Technologies–Restoration	Surface flow wetlands anaerobic denitrification. Groundwater is pumped and incorporated into a series of ponds. There are aerobic ponds used for oxidizing any trace amounts of ammonia that may

	be encountered, but the primary treatment system is the anaerobic pond. Cattails are used to generate organic detritus, which upon decay develops an anaerobic wetland environment. This environment in turn accommodates biodenitrification.
Duration of Treatment	Monitored for almost 5 years
Project Scale	Full scale
Issues Encountered	Arizona Department of Water Resources concerns regarding possible impacts to San Pedro River from groundwater pumping to the treatment wetland. A cattail caterpillar infestation delayed full operation. As a result, a molasses mixture was added to the system to test the performance temporarily. The infestation added time to accumulate plant detritus to act as the carbon source for the anaerobic surface flow wetlands. As a result of creating a surface wetland, wildlife began inhabiting the anaerobic wetland, creating what has been termed a potential coliform problem with the effluent discharge. The CERCLA agreement requires the substantive requirements of an NPDES discharge permit, which now includes coliform. The discharge is to a dry tributary to the San Pedro River.
Project Cost to Date	More than $1,000,000
Additional Info	We hope to achieve full startup of the treatment wetland sometime during the summer of 2002.

Response No. 10	Date 6/27/2002
Question	**Answer**
Name	Kathleen McCue
Telephone	(518) 402-8706
E-mail	kamccue@gw.dec.state.ny.us
Site Name	Fort Edward Landfill, DEC Site No.
Site Location	Fort Edward, New York
Previous Site Use	Municipal landfill ~1971–93; receiving industrial wastes included chlorinated solvents and PCBs
Size of Drainage Area	10 > 100
Constituents of Concern	Fe, up to 120 mg/L; vinyl chloride, avg 700 µg/L; other chlorinated VOCs, about 700 µg/L total; BTEX under 100
Regulatory Contact Name	John Strang
Regulatory Contact Telephone	(518) 402-9640
Regulatory Contact E-mail	jrstrang@gw.dec.state.ny.us
Plant Hardiness	4
Project Design and Application	Municipal landfill leachate containing high Fe and dilute volatile organics, especially vinyl chloride. Wetland design based on COD of about 125 mg/L, doubled (250 mg/L). COD selected since BOD was very low. Air stripper pretreatment based on avg influent vinyl chloride 700.
Flow Through System	1–10
Constituents after Treatment	Vinyl chloride and other VOCs less than 5 µg/L; PCB less than 65 µ/L; iron less than 0.3 mg/L
Flow Through System Units	gpm
Treatment Goals	New York SPDES discharge limits in CWTS effluent; eventual reduction of groundwater contaminants to below ambient water quality values in 6NYCRR Part 703.
Technologies–Municipal Waste Treatment	Groundwater extraction, passive leachate collection, subsurface flow wetland specifically using loam soil and phragmites (common reed)
Duration of Treatment	3 years 9 months
Project Scale	Full scale

Issues Encountered	Site is one of several politically visible satellite sites for disposal of wastes from General Electric's capacitor plants in Fort Edward and Hudson Falls. Regulatory issue: use of phragmites (giant reed) for wetland vegetation; phragmites considered invasive and destructive to local habitats. Special controls implemented in design to prevent migration of reeds out of the wetland.
Project Cost to Date	More than $1,000,000
Additional Info	Consultants for the CWTS design included URS Corporation, Buffalo, N.Y. and Harold Bates, Binghamton, N.Y.

Response No. 11	Date 6/27/2002
Question	**Answer**
Name	Cynthia Gianfrancesco, State Regulator
Telephone	(401) 222-4700, x 7126
E-mail	cgianfra@dem.state.ri.us
Site Name	Exxon Mobil Corp. East Providence Terminal
Site Location	East Providence, Rhode Island
Previous Site Use	Former petroleum storage facility
Size of Drainage Area	<1
Constituents of Concern	Maturation year
Principal Investigator Name	Joseph A. Abel
Principal Investigator Telephone	(401) 434-7356
Regulatory Contact Name	Cynthia Gianfrancesco, RI DEM
Regulatory Contact Telephone	(401) 222-4700, x 7126
Regulatory Contact E-mail	cgianfra@dem.state.ri.us
Plant Hardiness	6
Project Design and Application	Evaluation of the efficacy of a subsurface flow constructed wetland to remove benzene, toluene, ethylbenzene, and xylenes (BTEX) from groundwater discharging to a small perennial stream. Two treatment cells: cattail and phragmites.
Flow Through System	<1
Constituents after Treatment	Maturation year
Flow Through System Units	gpm
Treatment Goals	Benzene, 1 µg/L
Technologies–Other	Subsurface flow constructed wetlands employing an engineered self-contained matrix of wetlands plants (*Phragmites australis* and *Typha latifolia*), saturated substrates, and water to remove gasoline components (BTEX) in a small perennial stream.
Duration of Treatment	5 years
Project Scale	Field pilot
Issues Encountered	No
Project Cost to Date	$100,000 or less

Additional Info	This project was implemented in conjunction with source removal remediation and was implemented, in part, to determine the efficiency of the technology and if it could be implemented in a full-scale system in other areas on the site.

Response No. 12	Date 6/28/2002
Question	**Answer**
Name	Tim Reisch
Telephone	(757) 322-4758
E-mail	reischta@efdlant.navfac.navy.mil
Site Name	NNSY, New Gosport Landfill
Site Location	Portsmouth, Virginia
Previous Site Use	Former landfill along Paradise Creek, major tributary to the Elizabeth River, in which spent blast grit was disposed from 1969–70.
Size of Drainage Area	10 > 100
Constituents of Concern	Based on available information, the NNSY Project Management Team decided to proceed with the cleanup criteria of 400 mg/kg of lead for this area. This level is protective of human health and would allow unrestricted site access. The results of the draft ERA for Paradise Creek (CH^2MHILL, February 2001) determined that only a limited potential for adverse effects to aquatic life from direct exposure to chemicals in sediment and surface water exists in upper Paradise Creek (the headwaters of the creek, northwest of George Washington Highway). A limited number of inorganic chemicals and pesticides were detected in sediment and surface water at concentrations indicating a potential risk to benthic organisms. However, this potential for adverse effect was indicated primarily at a single sample location in the upper portion of a stormwater discharge drainage swale adjacent to the New Gosport Landfill, which was in an area identified for complete removal as part of the expanded scope of work. These chemicals were either not detected or were detected at much lower concentrations in sediment and surface water in the drainage immediately downstream of this sample location and in Paradise Creek. Polycyclic aromatic hydrocarbons (PAHs) were detected in sediment at concentrations just above screening values; however, most PAHs were ubiquitous in Paradise Creek, and it was concluded these compounds pose minimal potential for site-related risks to benthic

macro invertebrates. The results indicated that organic and inorganic chemicals in Upper Paradise Creek sediment and surface water do not pose a potential risk to higher trophic-level receptors via accumulation in the food web. Based on these results, it was concluded potential risks via food web exposure pathways are negligible and that chemicals from the New Gosport Landfill have a very limited potential to impact ecological receptors in Upper Paradise Creek. From these results, it was concluded (1) the potential for adverse effect is primarily localized in the upper portion of the drainage swale at the New Gosport Landfill, (2) there was very little transport of chemicals from the upper portion of this drainage to Paradise Creek, and (3) expanding the scope of the removal action and proposed site restoration would completely eliminate the identified potential risk.

Response No. 13	Date 6/28/2002
Question	**Answer**
Regulatory Contact Name	Mark Stephens, USEPA Region III
Regulatory Contact Telephone	(215) 814-3353
Regulatory Contact E-mail	stephens.mark@epamail.epa.gov
Project Design and Application	Removal of blast grit, confirmatory sampling for lead
Constituents after Treatment	Following the completion of the removal action, the lead concentrations in the New Gosport Landfill soils remaining at the site ranged 2.5–290 mg/kg (averaging 74.9 mg/kg) in Area A, 1.9–393 mg/kg (averaging 65.3 g/kg) in Area B, and 1.9–366 mg/kg (averaging 63.0 mg/kg) in Area C. All confirmatory sampling locations at Area A and all floor and southern wall locations at Areas B and C have been covered by a minimum of 1 foot of clean.
Treatment Goals	400 mg/kg for lead, based on HH exposure and future land use
Technologies–Hazardous/Solid	The blast grit was stabilized (in situ) to render the material nonhazardous for waste disposal.
Project Scale	Full scale
Issues Encountered	All the above
Project Cost to Date	More than $1,000,000

Response No. 14	Date 6/29/2002
Question	**Answer**
Name	Ted H. Streckfuss
Telephone	(402) 221-3826
E-mail	ted.h.streckfuss@usace.army.mil
Site Name	Line 1 – Iowa Army Ammunition Plant
Site Location	Burlington, Iowa
Previous Site Use	Active Army ammunition plant
Size of Drainage Area	10 > 100
Constituents of Concern	Primary contaminants: RDX and TNT explosives, in low part per billion (<30 ppb) concentrations
Regulatory Contact Name	Ted H. Streckfuss; no state involvement
Regulatory Contact Telephone	(402) 221-3826
Regulatory Contact E-mail	ted.h.streckfuss@usace.army.mil
Plant Hardiness	5
Project Design and Application	Wetland construction was initiated and overseen by USACE. The wetland is accepted by the client, local community, and USEPA, but the concept was met with derision at a wetlands conference. The cost was just for the earthmoving and the dam and gate construction. The costs were offset against the cost of backfilling the site. The project treated upwelling of contaminated groundwater and residual contamination in the saturated zone. The treatment is essentially a batch reactor; however the goal is to develop a flow-through system. Unanswered questions before flow through can be accomplished are (1) residence time, (2) channeling effects, (3) mode of contaminant uptake, (4) seasonal variation in effectiveness, (5) regulatory acceptance of contaminant levels in plant material, and (6) reduction of explosives compounds within surface flow wetland system, based upon individual plants' ability to produce the nitroreductase enzyme, instrumental in the degradation of the target contaminant. Sediment from a nearby lake that was silted in was used as seed bank for the project. The wetland was sited on pits, which would collect rainwater or surface water. Although the soil

	had low levels of explosives, the explosives would partition into water in the pits, creating a hazard for wildlife. Some carbon treatment is necessary because of a greater amount of runoff at times.
Flow Through System	10 > 100
Constituents after Treatment	<2 ppb for all constituents
Flow Through System Units	gpm, flow varies
Treatment Goals	Reduction of target compounds to <MCLs
Technologies–Hazardous Solid	Free water surface wetland flow
Duration of Treatment	3 years
Project Scale	Full scale. The treatment is somewhat cyclical with explosives being more effectively removed during warm months. There is some rebound during cold months when the flow of contaminants is greater than actual degradation processes. During the winter, some carbon treatment is necessary to polish the water.
Issues Encountered	The technology was very well received by the regulatory groups. The project used guidelines proposed by USEPA. The discharge levels mirror NPDES levels, and discharges are lower than what the NPDES would require. RDX and TNT are discharged at 2.0 ppb. The project manager feels that UV degradation accounts for a larger part of the destruction of the contaminant over phytodegradation or microbial degradation. One wetland flooded during an unseasonably large rain event, which added a huge volume of water to the wetland. The additional waters required treatment because phytoremediation had not yet been established. The completion of construction was timed to coincide with the growing season, and control of runoff may have prevented some of these problems.
Project Cost to Date	$100,001 > $1,000,000; $100,000 for treating the water with constructed wetlands would be much cheaper than filling in the pits with 20,000–30,000 cubic yards of soil. Costs involve analytical and pumping construction.

Response No. 15	Date 7/1/2002
Question	**Answer**
Name	Louis Howard
Telephone	(907) 269-7552
E-mail	louis_howard@envircon.state.ak.us
Site Name	Wetland Remediation System, Operable Unit 5
Site Location	Elmendorf AFB, Alaska
Size of Drainage Area	1 > 5
Constituents of Concern	Benzene ND – 8.5 mg/L, trichloroethene ND – 52 mg/L, sheen present on surface water
Principal Investigator Name	Joseph Williamson
Principal Investigator Telephone	(907) 552-2875
Principal Investigator E-mail	joseph.williamson@elmendorf.af.mil
Regulatory Contact Name	Kevin Oates
Regulatory Contact Telephone	(907) 271-6323
Regulatory Contact E-mail	Oates.Kevin@epamail.epa.gov
Plant Hardiness	3b
Project Design and Application	Natural attenuation of volatile compounds via seep collection, pumping system, overland flow cell, and wetland cell
Flow Through System	1 > 10
Constituents after Treatment	Benzene ND – 2.9 µg/L, tricholoroethene ND – 4.9 µg/L, and no sheen visible
Flow Through System Units	cfm
Treatment Goals	MCLs: benzene 5 µg/L, trichloroethene 5 µg/L, no sheen present, total aromatic hydrocarbons 10 µg/L, and total aqueous hydrocarbons 15 µg/L
Technologies–Other	Overland cell volatilizes contaminants, and wetland cell uses natural process (plants) to degrade contaminants present in water.
Duration of Treatment	5 years 1 month
Project Scale	Full scale
Issues Encountered	No
Project Cost to Date	More than $1,000,000

Additional Info	See USEPA Web site. http://www.epa.gov/superfund/sites/rodsites/1000155.htm# PA/ROD/R10-95/108rodinfo for Operable Unit 5 ROD ID EPA/ROD/R10-95/108 ROD date 12/28/1994 for more information.

Response No. 16	Date 7/2/2002, 10/23/02
Question	**Answer**
Name	Ted H. Streckfuss
Telephone	(402) 221-3826
E-mail	ted.h.streckfuss@usace.army.mil
Site Name	Hardfill 2C Wetland Treatment
Site Location	Offutt AFB, Nebraska
Previous Site Use	Base storage, old rail yard
Size of Drainage Area	<1
Constituents of Concern	Influent concentrations are in the low parts per billion (less than 200 ppb) for both constituents (TCE and dichloroethene [DCE])
Principal Investigator Name	URS Inc., Omaha
Regulatory Contact	RCRA
Plant Hardiness	5
Project Design and Application	The pilot study is designed to treat chlorinated volatile organics, specifically TCE and DCE.
Flow Through System	10 > 100
Constituents after Treatment	The treatment system is designed to meet the MCLs for the target contaminants (<5 ppb).
Flow Through System Units	gpm
Treatment Goals	MCLs
Technologies–Hazardous/Solid	Submerged flow treatment cells for VOC treatment
Duration of Treatment	1 month—planting in spring 2003
Project Scale	Field pilot under construction will be planted next season.
Issues Encountered	The technology was viewed favorably by both the regulatory community, as well as base personnel. May need an NPDES permit. During construction, concrete debris and liners were not manufactured correctly. RAB did not voice opposition.
Project Cost to Date	$100,001 > $1,000,000; $700K to date

Response No. 17	Date 7/2/2002
Question	**Answer**
Name	Charles Duerschner, P.E., Principal Investigator
Telephone	(402) 471-4206
E-mail	charles.duerschner@ndeq.state.ne.us
Site Name	Private owner wishes name to be kept confidential.
Site Location	Southeast Nebraska
Previous Site Use	N/A
Size of Drainage Area	10 --> 100
Constituents of Concern	$CBOD_5$, 120 mg/L
Plant Hardiness	In upper Midwest, wetland plants go dormant for six months.
Project Design and Application	To provide secondary treatment of domestic wastewater under NPDES permit.
Flow Through System	10 --> 100
Constituents after Treatment	$CBOD_5$, 2–10 mg/L
Flow Through System Units	1000 gallons/day
Treatment Goals	NPDES secondary treatment
Technologies–Stormwater Control	N/A
Technologies–Municipal Waste Treatment	Settling tanks, subsurface flow constructed wetland, sand filters
Duration of Treatment	5 years, 6 months
Project Scale	Full scale
Issues Encountered	Constructed wetland chosen as best aesthetic option in residential and golf-course community. Also chosen for low O&M needs. State order required a new system be built after previous community septic system failed.
Project Cost to Date	$100,001 --> $1,000,000
Additional Info	The first constructed wetland built in Nebraska and the only one on which the state has good data. Two other wetlands have been built more recently, both for treating domestic wastewater. Most NH_3 removal occurs in sand filter. The constructed wetland has experienced some plugging problems in short.

Response No. 18	Date 7/2/2002
Question	**Answer**
Name	Eric A. Nelson
Telephone	(803) 725-5212
E-mail	eric.nelson@srs.gov
Site Name	Savannah River Site
Site Location	Aiken, S.C.
Previous Site Use	Forested
Size of Drainage Area	10 > 100
Constituents of Concern	Cu, avg. 50–200 ppb
Plant Hardiness	8
Project Design and Application	Metal (Cu and Hg) and toxicity removal from NPDES
Flow Through System	1 > 10
Constituents after Treatment	Cu >10 ppb
Flow Through System Units	million gallons per day
Treatment Goals	NPDES discharge limits; Cu, 22 ppb; Hg 12 ppt
Technologies–Stormwater Control	Retained in basin and bleed off through wetlands
Technologies–Industrial Waste Treatment	Surface flow wetland system
Duration of Treatment	2 years
Project Scale	Full scale
Issues Encountered	New technology for waste treatment with state
Project Cost to Date	More than $1,000,000
Additional Info	Eight 1-acre cells, connected as pairs

Response No. 19	Date 7/3/2002
Question	**Answer**
Name	Arati Kolhatkar
Telephone	(630) 420-5332
E-mail	arati.kolhatkar@bp.com
Site Name	Casper
Site Location	Casper, Wyoming
Size of Drainage Area	1 > 5
Constituents of Concern	Benzene: 0.4 ± 0.2 mg/L
Principal Investigator Name	Joe Deschamp
Principal Investigator Telephone	(307) 261-4211
Principal Investigator E-mail	deschampja@bp.com
Plant Hardiness	4a–4b
Project Design and Application	Reduction of benzene concentration in the wetland effluent to 0.05 mg/L (the concentration limit for discharge to the POTW).
Flow Through System	1 > 10
Flow Through System Units	gpm
Treatment Goals	Meet benzene's concentration limit (0.05 mg/L) for discharge to the POTW.
Technologies–On-Site Wastewater	Passing contaminated water through an oil-water separator followed by an air stripper. The water is then discharged to the POTW via two equilibration tanks.
Duration of Treatment	4 months
Project Scale	Field pilot
Issues Encountered	Regulatory: Protect the North Platt River from contaminated groundwater
Project Cost to Date	$100,000 or less

Response No. 20	Date 7/3/2002
Question	**Answer**
Name	Gretchen Pikul
Telephone	(907) 269-3077
E-mail	gretchen_pikul@envircon.state.ak.us
Site Name	Eareckson Air Station
Site Location	Shemya Island, Alaska
Previous Site Use	The SS07 Engineered Wetland lies in the northwest portion of Shemya Island, ~400 feet southwest of Tank 123, within the confines of Source Area SS07, which originally encompassed five unlined earthen ponds and their connecting shallow surface ditches. The SS07 drainage (five ponds and their drainage channels) and its tributaries represent the dominant surface water drainage in the area. The ponds were designed and constructed to intercept oil-contaminated surface waters draining from areas to the northeast (the power plant) and northwest (Source Area ST46, a fuel tank farm) before they reached the Bering Sea. The engineered wetland is situated on the former site of Pond 3, near the middle of the SS07 drainage area.
Size of Drainage Area	<1
Constituents of Concern	The SS07 Engineered Wetland system design was based on the remedial objective of eliminating the presence of hydrocarbon sheen from the surface water. Year 1999/2000 results: inlets DRO values range 0.190–0.260 mg/L (no surface water quality standard); fluorine, ND–0.127 µg/L (3.9 µg/L surface water quality standard); phenanthrene, ND–0.0625 µg/L (surface water quality standard of 6.3 µg/L). Cells 1993 and 2000 results: 0.110 mg/L and 0.100 mg/L, ND (no surface water quality standard); outlets A and B had no constituents detected above the method reporting limits. Sediment results have many petroleum constituent detects, and the reports can be provided in CD form.
Principal Investigator Name	Larry Opperman, 611th CES/CEVR – Air Force
Principal Investigator Telephone	(907) 552-7697
Principal Investigator E-mail	Larry.Opperman@ELMENDORF.af.mil

Regulatory Contact Name	Gretchen Pikul
Regulatory Contact Telephone	(907) 269-3077
Regulatory Contact E-mail	gretchen_pikul@envircon.state.ak.us
Project Design and Application	In 1998, an engineered wetland was constructed over the top of petroleum-contaminated sediments at Site SS07 to intercept and treat surface water flow containing hydrocarbons from nearby sources. The wetland system consists of two ponds (the inlet and outlet deep mixing areas) and a raised wetland area of approximately 106 by 112 feet, which is divided into two treatment cells. Water enters the inlet deep mixing via four channels. Suspended sediment in the water should settle out in this deep mixing area. The water then flows from the inlet deep mixing into the wetland treatment cells. The water depths in the two wetland treatment cells were designed to be 6–36 inches. The system was designed such that, as water passes through the wetland, it would be dispersed and slowed by vegetation to allow contaminants to become trapped or adsorbed by plant leaves, stems, and roots, or bound in the sediment. The interior berm separating the treatment cells was designed to encourage channel flow and prevent short-circuiting (preferentially flowing in unintended channels). The water finally flows through the outlet, deep mixing, out the discharge culvert, and into the drainage channel. A series of four absorbent booms installed in the outlet drainage channel absorb any free product that may have passed through the SS07 Engineered Wetland.
Flow Through System	10 > 100
Constituents after Treatment	The two outlets have no constituents detected above the method reporting limits.
Flow Through System Units	Design HRT was a minimum of one day (based on flows ranging 37.5–127 gpm with depths 1–3 feet).
Treatment Goals	18 AAC 70 surface water quality standards
Duration of Treatment	4 years
Project Scale	full scale
Project Cost to Date	$100,001 > $1,000,000

Additional Info	Site reports and optimization plans on CD can be easily forwarded for reference. If interested in copies, please e-mail or call with an address.

Response No. 21	Date 7/5/2002
Question	**Answer**
Name	Karl Hoenke
Telephone	(925) 842-9259
E-mail	karlhoenke@chevrontexaco.com
Site Name	Jayhawk
Site Location	Near Galena, Kansas
Previous Site Use	WW II munitions manufacturer, fertilizer and specialty chemicals
Size of Drainage Area	>100
Constituents of Concern	Nitrates, 15–20 ppm
Project Design and Application	Reduce nitrate in stormwater runoff from 15–20 ppm to less than 10 ppm (mass loading arguments not accepted).
Flow Through System	100 > 1000
Constituents after Treatment	nitrates vary, ND–5 ppm
Flow Through System Units	gpm
Treatment Goals	NPDES-driven
Technologies–Stormwater Control	Leaky 60-year-old concrete piping, collection only
Duration of Treatment	3 years, 8 months
Project Scale	Full scale
Issues Encountered	Regulatory: 8-acre parcel had to be diked and separated from 120-acre lake/wetland to provide a sampling point with which to show the nitrates degrade. The lake was ND. Determined to be a waste of money.
Project Cost to Date	$100,001 > $1,000,000
Additional Info	See issues encountered. This was an unnecessary project from a technical standpoint. Nevertheless, it works and meets state criteria.

Response No. 22	Date 7/9/2002
Question	**Answer**
Name	Dave Turner
Telephone	(865) 594-5541
E-mail	dave.turner@tn.state.us
Site Name	SVC
Site Location	Cagle, Tennessee
Previous Site Use	Coal mine
Size of Drainage Area	>100
Constituents of Concern	Fe, 100 mg/L
Principal Investigator Name	Martin Stearns
Principal Investigator Telephone	(307) 685-6124
Principal Investigator E-mail	steansm@kenenergy.com
Regulatory Contact Name	Dave Turner, TDEC
Regulatory Contact Telephone	(865) 594-5541
Regulatory Contact E-mail	dave.turner.@state.tn.us
Project Design and Application	Mass loading (Fe, Mn, and acidity)
Flow Through System	100 > 1000
Constituents after Treatment	Fe < 2 mg/L
Flow Through System Units	gpm
Treatment Goals	NPDES effluent guidelines, elimination of toxicity (acid loading)
Technologies–Stormwater Control	Diversion of stormwater from treatment system
Technologies–Mine Drainage	Anoxic limestone drain, oxidation and aerobic constructed wetlands
Duration of Treatment	6 years and 6 months
Project Scale	Full scale
Issues Encountered	Regulatory issues: water quality standards and NPDES effluent limitations
Project Cost to Date	$100,001 > $1,000,000
Additional Info	Project success has been published in ASMR annual meeting 2001.

Response No. 23	Date 7/17/2002
Question	**Answer**
Name	Verne Brown
Telephone	(916) 339-3898
E-mail	vwbrown@earthlink.net
Site Name	Rising Star Mine
Site Location	Shasta County, California
Size of Drainage Area	<1
Constituents of Concern	Cadmium, 0.072–0.47 mg/L
Regulatory Contact Name	Phil Woodward, California RWQCB
Project Design and Application	Mass loading (Cd, Cu, Fe, Zn, Pb, acidity, sulfate) for ARD treatment
Flow Through System	1 > 10
Constituents after Treatment	Cadmium, 0.009–0.303 mg/L
Flow Through System Units	gallons per minute
Treatment Goals	30-day avg. daily max
Technologies–Mine Drainage	Sulfate-reducing bacteria in a compost substrate
Duration of Treatment	19 months
Project Scale	Field pilot
Issues Encountered	Remote location without power, high potential for vandalism. Strong desire to use a passive technology to minimize O&M costs.
Project Cost to Date	$100,000 or less
Additional Info	Pilot test cell is a vertical upward flow cell. Pilot treatment cell contains approximately 80 yd^3 of compost overlying a limestone gravel layer. ARD enters the cell at the bottom and passes upward through the substrate. Overlying the substrate is a pond to permit the settling of precipitates. Preliminary data used to identify an optimal size for the primary treatment cells. A follow-on test would provide data for the secondary treatment cell design.

Response No. 24	Date 7/23/2002
Question	**Answer**
Name	Gerald J. Rider, Jr., P.E.
Telephone	(518) 402-9551
E-mail	jxrider@gw.dec.state.ny.us
Site Name	Fort Edward Landfill
Site Location	Leavy Hollow Road, Fort Edward, NewYork 12828
Previous Site Use	Industrial/municipal landfill
Size of Drainage Area	10 > 100
Constituents of Concern	A 1995–97 investigation found shallow groundwater to be contaminated with up to 10 ppm of chlorinated solvents, principally vinyl chloride and 1,2-dichloroethylene. Iron exceeded 300 ppm in some samples, and the NYSDEC anticipated that it would complicate the operation of a conventional physical-chemical treatment plant for groundwater. In May 1999, the chlorinated solvent level was found to be up to 100 ppb (vinyl chloride, 20 ppb; 1,2-DCE, 22 ppb; toluene, 14 ppb; total xylenes, 33 ppb). In June 2002, the chlorinated solvent level was measured to be up to 600 ppb (vinyl chloride, 230 ppb; 1,2-DCE, 314 ppb; benzene, 20 ppb; total xylenes, 27 ppb). June 2002 results show a lack of dilution of the leachate by groundwater as the collection trench pump is under repair.
Principal Investigator Name	John R. Strang, P.E.
Principal Investigator Telephone	(518) 402-9551
Principal Investigator E-mail	jrstrang@gw.dec.state.ny.us
Plant Hardiness	4 (-30 to -20ºF)
Project Design and Application	The design of the Fort Edward Landfill Constructed Wetland Treatment System is based on the principle of subsurface flow through a matrix of roots of *Phragmites australis* (giant reed) in clay loam soil as the treatment media. The soil provides chelation and ion exchange; the plants increase the horizontal permeability of the soil, provide organic matter to promote biodegradation, and promote oxygen–carbon dioxide exchange through porous tissue. To treat 25 gpm of leachate (solvents) and

	groundwater, the system includes 4 acres of constructed wetland, divided into three beds of equal size, operated in parallel. A "polishing pond," ½ acre in size, completes treatment before discharge to a tributary of the Hudson River. Design loads include 741 mg/L (ppb) vinyl chloride; 852 ppb 1,2-DCE; 256 ppm chemical oxygen demand; and 70 ppm iron.
Flow Through System	10 > 100
Constituents after Treatment	For chlorinated solvents, the values have been found at less than the detection limit of 10 ppb. The metals effluent values are exceeded for iron. Iron levels in all background analyses exceed the discharge permit limit of 300 ppb.
Flow Through System Units	gallons per minute
Treatment Goals	Meet effluent limitations and monitoring requirements as set by the New York State Department of Environmental Conservation, based on discharge to the Glens Falls Feeder Canal. A copy of these limits can be furnished upon request.
Technologies–Hazardous/Solid	Biodegradation and promotion of oxygen–carbon dioxide exchange through porous tissue.
Technologies–Other	Feremede is added to the pumped leachate/ groundwater to keep iron in suspension and to allow settling out in polishing pond rather than in piping.
Duration of Treatment	3 years and 11 months (since September 1998)
Project Scale	Full scale
Issues Encountered	No. The original chosen remedy—slurry wall containment with groundwater pump and treat—was not constructed because site continued to be used as a municipal landfill for some years following industrial use. The use of a constructed wetland was chosen once the landfill was closed by the municipality and problems with a slurry wall/P&T remedy for an industrial landfill approximately ¼ mile away were documented.
Project Cost to Date	More than $1,000,000

Response No. 25	Date 7/24/2002
Question	**Answer**
Name	Greg Handly
Telephone	(518) 897-1243
E-mail	gjhandly@gw.dec.state.ny.us
Site Name	Clinton County Landfill
Site Location	Mooers, New York
Previous Site Use	Former municipal landfill
Size of Drainage Area	10 > 100
Constituents of Concern	Inorganics, metals, and VOCs. TDS, 1600 mg/L; Fe, 25 mg/L; VOCs, 225 µg/L, July 1996. TDS, 656 mg/L; Fe, 21 mg/L; VOCs, 6 µg/L, April 2002.
Regulatory Contact Name	Same as above
Plant Hardiness	4 acres
Project Design and Application	Six stepped impoundments accepting subsurface leachate exiting the capped landfill. Typical landfill leachate inorganics, metals, and low-level volatile organics enter the impoundments and are reduced by dispersion, dilution, phyto, and bioremediation.
Flow Through System	10 > 100
Constituents after Treatment	TDS, 706 mg/L; Fe, 0.18 mg/L; VOCs, <5 µg/L
Flow Through System Units	gpm
Treatment Goals	Groundwater standards
Duration of Treatment	6 years
Project Scale	Full scale
Issues Encountered	No
Project Cost to Date	$100,001 > $1,000,000
Additional Info	Following capping initial leachate volume caused surface exposure and slow vegetative growth in first two impoundments. At this time, all impoundment vegetation has recovered, and no surface leachate is visible.

Response No. 26	Date 10/4/2002
Question	**Answer**
Name	Paul Eger
Telephone	(651) 296-9549
E-mail	paul.eger@dnr.state.mn.us
Site Name	Dunka Mine
Site Location	Rabitt, Minnesota
Previous Site Use	Open pit iron mine, five wetland systems were built to treat waste rock stockpile.
Size of Drainage Area	10 > 100
Constituents of Concern	Nickel is the primary CoC, 1.0–10.0 mg/L; copper, 0.1–1.0 mg/L; zinc, 0.1–1.0 mg/L. Four of the sites produce circumneutral draining, and one produces acid drainage pH ~4.0–5.0.
Regulatory Contact Name	Richard Clark
Telephone	(651) 296-8828
E-mail	Richard.clark@pca.state.mn.us
Plant Hardiness	Northern Minnesota
Project Design and Application	A surface flow pilot system was built, and design criteria for nickel removal was developed. The available area was a key factor in the final design.
Flow Through System	100 > 1000 gpm
Constituents after Treatment	All systems remove metal ranging 50–90%.
Flow Through System Units	gpm
Treatment Goals	The site is covered by an NPDES permit. Concentrations are related to toxicity and very general ranges of Ni, 0.21–0.48 mg/L. Copper is 0.023 mg/L, and zinc is 0.34 mg/L.
Duration of Treatment	4–10 years
Project Scale	Full scale
Issues Encountered	There was initial skepticism over the ability of the technology.
Project Cost to Date	More than $1,000,000

Response No. 27	Date 12/12/2002
Question	**Answer**
Name	Dr. Robert Kadlec
Telephone	(734) 475-7256
E-mail	rhkadlec@chartermi.net
Site Name	Amoco Refinery
Site Location	Casper, Wyoming
Previous Site Use	Amoco's former Casper Refinery was in continuous operation 1912–91. The northern boundary of the 350-acre site is the North Platte River. Petroleum hydrocarbons were released into the subsurface from many different locations during the period of operation. Over 10 million gallons of free product (LNAPL) have been recovered from the water table, and it has been estimated that 20 million gallons remain. A pilot-scale subsurface flow wetlands system was built at the site to test the concept that a constructed wetland could be used to treat recovered groundwater. The system was designed by Phytokinetics, Inc., in cooperation with Wetland Management Services.
Size of Drainage Area	NA (Groundwater treatment)
Constituents of Concern	Benzene, total petroleum hydrocarbon, MTBE
Project Design and Application	The pilot-scale wetland system was made up of four treatment cells packed with sand operated from July 2001 to early January 2002. Influent water for the system was a slipstream from the large-scale oil/water separator that is currently being used to treat recovered groundwater, and effluent from the treatment cells was pumped to a large-scale air stripper. The cells were operated in an upward vertical flow mode at a flow rate of approximately 5.5 m^3/d. The mean hydraulic detention time for the cells was approximately one day. Two of the cells were subjected to forced subsurface aeration using coarse bubble aerators at the rate of 14 standard liters per minute. A plastic sheet greenhouse was used to shelter the wetland in January. Water flowing into and out of the treatment cells was sampled at regular intervals, and the samples were analyzed for benzene and other organics, including

	total petroleum hydrocarbons (TPH) and methyl *tert*-butyl ether (MTBE) as well as for iron and calcium. The cells were also monitored for flow rate, water temperature, pH, and dissolved oxygen. *Dimensions:* 4 beds: each 7.0 m long x 1.7 m wide and 0.90 m deep *Substrate:* 2 beds: 15 cm sod, 55 cm sand, 15 cm coarse gravel, geotextile, 5 cm sand. 2 beds: 60 cm sand, 10 cm pea gravel, 15 cm coarse gravel, geotextile, 5 cm sand. *Liner:* concrete *Plants:* willows (*Salix* spp.), bulrush (*Scirpus* spp.),soft rush (*Juncus* spp.), reeds (*Phragmites australis*) *Inlet distribution:* Below ground, perforated PVC pipes *Outlet collection:* Horizontal well screen, set at the elevation of the matrix surface, and then lowered to 3 inches below the matrix for winter.
Flow Through System	5.5 m^3/day
Constituents after Treatment	Table 1 shows the performance results for four cells for six months, August–January. Effluent standards for benzene were met in aerated cells. High removals of benzene, BTEX, and TPH were achieved despite very short detention times. The high rate constants are attributed to degradation and volatilization. MTBE showed lesser removal and lower rate constants, which were, however, comparable to those expected for BOD in municipal systems. Aeration improved performance for all hydrocarbon constituents. A full-scale system is under construction, based upon these pilot project results. A horizontal subsurface flow wetland with forced subsurface aeration will be a central component of that system. Horizontal subsurface flow (instead of UVF) will be used, to prevent short-circuiting problems. The matrix will be mostly gravel (rather than the predominantly sandy matrix used in the pilot). The gravel will provide the high hydraulic conductivity necessary for the horizontal SSF. The top of the Phase I system will be covered with a 6-inch thick layer of compost,

	which will thermally insulate the system to prevent freezing in winter.
Flow Through System Units	m^3/day
Treatment Goals	0.050 mg/L benzene in the outlet
Duration of Treatment	July 2001–January 2002
Project Scale	Pilot scale
Issues Encountered	MTBE showed lesser removal and lower rate constants, which were, however, comparable to those expected for BOD in municipal systems. Aeration improved performance for all hydrocarbon constituents.
Additional Info	

Table 1. Performance of the Casper vertical flow constructed pilot wetlands, including first-order rate constants and percent reduction

	Air		No Air	
	Sod	**No Sod**	**Sod**	**No Sod**
Temperature, C°	13.7	14.3	13.2	13.1
HRT, days	0.92	1.58	0.96	1.02
Depth, m	0.88	0.88	0.88	0.88
Benzene				
K, day^{-1}	2.4	2.2	1.7	1.5
Cin, mg/L	0.30	0.30	0.30	0.30
Cout, mg/L	0.040	0.040	0.097	0.112
Removal, %	87	87	68	63
BTEX				
K, day^{-1}	1.9	1.6	1.5	1.4
Cin, mg/L	1.26	1.26	1.26	1.26
Cout, mg/L	0.14	0.114	0.42	0.435
Removal, %	89	91	67	65
TPH				
K, day^{-1}	3.4	3.2	3.1	2.6
Cin, mg/L	44.3	44.3	44.3	44.3
Cout, mg/L	2.2	1.0	1.68	4.35
Removal, %	95	98	96	90
MTBE				
K, day^{-1}	0.46	0.32	0.24	0.17
Cin, mg/L	1.26	1.26	1.26	1.26
Cout, mg/L	0.87	0.91	1.00	1.07
Removal, %	31	28	21	15

APPENDIX B

Acronyms

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ACRONYMS

ALD	anoxic limestone drain
ALR	areal loading rate
API	American Petroleum Industry
BOD	biochemical oxygen demand
BOD_5	5-day biochemical oxygen demand
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
COD	chemical oxygen demand
CWA	Clean Water Act
CO	carbon monoxide
DCE	dichloroethene
EA	environmental assessment
EIS	environmental impact statement
ESA	Endangered Species Act
FAC	facultative plants
FACU	facultative upland plants
FACW	facultative wetland plants
FONSI	finding of no significant impact
FWS	free water surface
HDPE	high-density polyethylene
HF	horizontal flow
HLR	hydraulic loading rate
HRT	hydraulic retention time
ITRC	Interstate Technology & Regulatory Council
LLDPE	linear low-density polyethylene
mgd	million gallons per day
NEPA	National Environmental Policy Act
NFESC	Naval Facility Engineering Service Center
NMFS	National Marine Fisheries Service
NPDES	National Pollution Discharge Elimination System
NPS	nonpoint source
O&M	operations and maintenance
ODEQ	Oklahoma Department of Environmental Quality
ORP	oxidation-reduction potential
OBL	obligate wetland plants
OWRB	Oklahoma Water Resources Board
PAH	polycyclic aromatic hydrocarbon
PC	polycarbonate
PCB	polychlorinated biphenyl
PCE	perchloroethylene
POTW	publicly owned treatment works
PPE	polypropylene
PVC	polyvinyl chloride
RAPS	reducing alkalinity-producing wetlands

RCRA	Resource Conservation and Recovery Act
SF	surface flow wetland
SIC	standard industrial classification
SRB	sulfate-reducing bacteria
SSF	subsurface flow wetland
TCE	trichloroethylene
TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TN	total nitrogen
TSS	total suspended solids
UPL	upland plants
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
VF	vertical flow
VSB	Vegetative Submerged Bed
VOC	volatile organic compound
WQS	water quality standard

APPENDIX C

Response to Comments from ITRC Points of Contact and Peer Reviewers

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Review of *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands*, prepared by the Interstate Technology & Regulatory Council Wetlands Team

Anna Knox, Savannah River Site

During the past decades, the prevention of environment pollution and cleanup of contaminated media have become worldwide environmental priorities. The goal of constructed treatment wetlands is not only to enhance the timely degradation, transformation, remediation, or detoxification of pollutants by biological/chemical means, but also to protect environment quality. Therefore, the importance of this document is significant. This document is written clearly and provides all necessary information on this emerging technology that will be useful to a wide range of users, regulators, industry, consultants, researchers, and students. However, I have a few suggestions/comments that could improve the quality of this document.

Suggestions/comments:

1. Page 5—For the section “Wetland Plants” or as an additional appendix, provide photos of some more representative plants for wetland ecosystems. For example, attached is the photo of a water lily (*Nymphaea sp.*) as an example of floating leafed plants.

Response: Thank you for the comment; however, the team has chosen not to use a single photo.

2. Figure 2-9—Label each zone as on Figure 2-8, i.e., subsoil, root zone, litter, water, air. The word *sediments* should be moved to the litter zone.

Response: The zones appear to be labeled appropriately. The term *sediments* in the aqueous zone is demonstrating the process that metals removal follows through the sedimentation process.

3. Paragraph 2.3.3/page 16—A table with a classification and structure of hydrocarbons would be suitable and useful to readers.

Response: Even though additional information would be useful, it is not suitable to elaborate more on the classification and structure of hydrocarbons in this document. It does not appear to add to the value of the technical nature of the document and will not assist the reader to understand the relationship the structure and classification of a hydrocarbon has on the applications we discuss.

4. Table 2-2—The addition on the removal of Hg (a study case of Dr. John Gladden’s group from the Savannah River Site, Aiken, S.C. Dr. Gladden provided this information to Steve Hill via e-mail.)

Response: Thank you for the additional information. The team has updated the document with Gladden’s work.

5. Table 2-2—Se, under “Removal mechanism” add “Volatilization.”

Response: Selenium does volatilize as dimethylselenide. The team has added volatilization to the table.

6. Table 2-2—The presented removal mechanisms are too general. It would be good to at least state under what condition (e.g, pH/Eh) these mechanisms occur.

Response: We have provided references for each of the metals. Each reference describes the measured conditions affecting the removal/precipitation.

Constructed Treatment Wetlands
QA/QC Review and Comments
Paul Hadley and Bart Faris

Executive Summary

7. What are the barriers to deployment?
   Unlike terminology
   Lack of understanding
   Perceived ineffective
   Difficulty in securing permits
   Regulatory (well addressed in the document)

Response: This is a mature technology being applied to additional waste streams and new contaminants. Doing this requires a better understanding of the mechanisms contributing to the treatment.

8. How has this document addressed or provided a solution to these barriers? Should be stated in the Executive Summary with detailed description in the document.

Response: The team has since delineated specific recommendations in Section 9.0 and included a bulleted list in the Executive Summary. These will be highlighted in the Internet training as well.

QA/QC Questions as They Relate to ITRC's QA/QC Document

9. Are there policies from states (specifically TM states) that would impede or deter implementation of constructed wetlands? If so, please discuss.

Response: See Section 9.0

10. How have the case studies presented impacted programs, states, projects, or approval? Did X case study show the barriers were reduced or increased?

Response: Discussion of case studies is contained throughout the text. In addition, case studies are included as Appendix A, which also contains a reference list with contact information so readers can contact the operators in the future. Wetlands, since they take a period of time to establish, often don't have performance data for several years after maturity of the plants. The

case studies in Appendix A show an increasing level of confidence in applying wetlands as a treatment technology in new situations and to new contaminants.

11. Has the team addressed the question "What does a regulator need to know or require in order to approve/disapprove this technology?" Is there anyway you can point this out, or do the decision trees answer this?

Response: The decision trees describe those elements required to evaluate the applicability of wetlands for the site. If all is positive, this should allow approval of the technology. This doesn't mean that the system as designed or tested will clean the site up to the agreed upon cleanup goals.

12. Are the "critical elements" addressed?
    -Regulatory is there.
    -Health and Safety isn't there, but it might not apply.

Response: Health and safety always applies as part of the exposure assessment. A distinction is made on the use of surface flow wetlands versus. subsurface flow wetlands based on exposure. Maintenance personnel are part of this exposure assessment.

13. ITRC format is there.

Response: Thank you

14. Advantages and disadvantages are there but not that clearly spelled out where someone could find it in the Table of Contents.

Response: See Section 9.9 in the Table of Contents.

15. Performance is there (Sections 6.1 and 9.4) but could be elaborated upon in more detail to answer the questions in the QA/QC document under critical elements for performance.

Response: The following tables discuss the characteristics of wastewater according to origin and present treatment efficiencies for each contaminant in a particular waste stream. Section 6.1 further discusses other performance parameters as well.

- Table 4-2. Typical stormwater pollutant concentrations from nonpoint sources
- Table 4-3. Surface flow wetland treatment of stormwater at selected sites
- Table 4-4. Typical characteristics of municipal wastewater most often treated in constructed wetlands
- Table 4-5. Typical background concentrations of various parameters found in SF wetlands treating municipal waste
- Table 4-6. Typical municipal wastewater characteristics and removal efficiencies
- Table 4-7. Typical characteristics of mine drainage water
- Table 4-8. Reported removal efficiencies from case studies collected in 2002
- Table 4-9. Typical range of removal in wetlands constructed to treat mine drainage

- Table 4-10. Typical pollutant concentrations in a variety of industrial wastewaters
- Table 4-11. Typical removal efficiencies of contaminants at industrial facilities
- Table 4-12. Landfill leachate characteristics and removal efficiencies
- Table 4-13. Reported concentrations of groundwater contaminants from two case studies from Fort Edward, New York
- Table 4-14. Landfill leachate characteristics
- Table 4-15. Leachate removal efficiencies for a constructed wetland in Clinton County, N.Y.
- Table 4-16. Common constituents and treatment efficiencies in agricultural wastewaters

16. Stakeholder input is there. Do you need stakeholder input for each specific decision tree or are the stakeholder concerns the same for each constructed wetlands application?

Response: They appear to be the same regardless of the application.

General Document Comments

17. In Introduction: Since constructed wetlands are "ideally suited," why hasn't there been more deployment? Need to spell out barriers to implementation and provide solutions or suggestions to overcome those barriers (lack of understanding, long-term treatment, sizing, costs, monitoring etc.).

Response: Paragraphs 2 and 3 of the Introduction explain that the maturity of the technology warrants new and innovative applications. Without saying as such, lack of understanding inhibits wetlands use as it does most other innovative applications of mature technologies. For instance, bioaugmentation has been used in tanks and ex situ as a water treatment for many years. Only recently have we begun to introduce the same concepts into the environment.

18. Have you verified all references, and are they properly cited (I saw a few without correct punctuation and citation)? For instance, in Section 2.1.1, the second paragraph needs a reference for CWA, and in 2.1.2, the reference in the second to last paragraph has no date. Finally, there is a lot of general description of the technical aspects of constructed wetlands that should be referenced. For instance, in Section 2.1.2 on soils, numerous references should be included on the definition of soils.

Response: Yes, thank you.

19. GREAT FIGURES AND TABLES! Excellent description of what they are and how they work.

Response: Thank you.

20. GREAT DECISION TREES. Very practical and useful.

Response: Thank you.

21. Need to double check spelling, formatting, and punctuation throughout the document.

Response: Thank you.

22. Great info on technical, terminology, and how constructed wetlands work, but I found little that addresses the barriers and why we don't see more constructed wetlands installed. Need to provide solutions to the barriers. For example, on page 37, last paragraph, it states that "improper management and maintenance" may not reach limits for N and P. Why? This would be a good place to say which bad design and maintenance practices caused failure, thus causing regulatory skepticism.

Response: The sentence immediately following your reference sentence reads, "If discharge limits are low, harvesting vegetation may be required to remove the nitrogen and phosphorus released during plant senescence." This means that if the treatment limits are low, then your must remove the plants that accumulate the N and P in the plant mass. It may be released back into the water through death and decomposition of the plant matter or respiration from the plant. Senescence=the act of growing old.

Illinois, EPA

23. Historically, the IEPA, Bureau of Water, has required that industrial facilities provide some type of liner system for a wetlands used for treatment. The sites were not allowed to discharge directly to an unlined system.

Response: The document provides for the use of liners.

24. In Illinois, this would be considered a treatment works and would require a state construction and operating permit from the IEPA's Bureau of Water. Depending on the situation, the operation of the system would be covered under the state permitting program or the NPDES permit program if there were surface discharges.

Response: Thank you**.**

25. The actual discharge limitations would dictate or drive what treatment could be used. In the case of a wetland system, it might work for some sites but not others. In other words, treatment using wetlands may not be adequate to meet the permit limitations. If the permit limitations could not be met, the application would have to be denied.

Response: The team agrees and points users to the performance tables for various applications. Very generally, these performance values could be used as an initial screen.

George Dasher
West Virginia Department of Environmental Protection
Charleston, West Virginia

26. Section 2.3.3, Hydrocarbons, fourth paragraph, last sentence—This list describes all napthalenes and it is a common PAH and is water-soluble.

Response: Thank you. Yes.

27. Section 2.3.3, Hydrocarbons, eighth paragraph, last sentence—Dichloroethylene is an intermediate degradation product between tetrachloroethylene and trichloroethylene.

Response: More accurately, dichloroethylene is a degradation product of trichloroethylene. It is a primary intermediate and has been included in the text in its correct position.

New Jersey
Municipal Finance and Construction Element (MFCE)

28. The Municipal Finance and Construction Element (MFCE) has reviewed the technical document entitled *Technical and Regulatory Guidance Document for Constructed Treatment Wetlands* dated April 2003, prepared by the Interstate Technology & Regulatory Council Wetlands Team. For municipal wastewater treatment and stormwater projects seeking funding through NJDEP, the applicant who wishes to use constructed treatment wetlands (CTW) will be required to provide a planning report that addresses engineering, environmental, and cultural resource requirements based upon N.J.A.C. 7:22-3, 4 and 10 et seq. Based upon review of the technical document, it has been noted that most of the following comments have been addressed in terms of general CTW application. However, for projects specifically seeking NJDEP funding, the following information will be required.

- Siting of the wetlands cell(s) and current land use where constructed treatment wetlands is to be located
- Climatic considerations
- Use of and establishment of native plant species approved by NJDEP
- Potential LURP oversight of the CTW
- Harvesting and disposal of wetlands vegetation
- Maintenance of the wetlands cell to prevent mosquito breeding and anoxic conditions
- Potential odor issues and proximity to sensitive receptors
- Impacts on surrounding ecosystems
- Presentation of a cost-effective analysis that presents other alternatives compared to the use of the CTW. The use of the CTW must be the most cost-effective alternative that provides a water quality benefit.

If you have any further questions, please contact the MFCE, Bureau of Program Development and Technical Services at 3-1170.

Response: Thank you for the additional and New Jersey–specific information.

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29. Page 106, Table 8-1—Add Migratory Bird Treaty Act.

Response: This federal act intends to protect the movement and reduce harm to migratory birds, however constructed treatment wetlands are typically an insignificant force regarding migratory wildlife. This is not intended to minimize the law only to put it in perspective to typical constructed treatment wetlands. This federal law applies at least to the same extent as the Endangered Species Act and has been added. Thank you for the comment.

30. Page 118, 9.6.2, Ecological Risk Assessment, first paragraph—Add "Ohlendorf, 1989" following "Knight, 1996."

Response: Thank you.

31. Page 118, 9.6.2, Ecological Risk Assessment, fourth paragraph—Delete "Federal Register, Vol. 63, no. 93, page 26846."

Response: Thank you. The Federal Register citation has been deleted, and the proper citation included.

32. Page 118, 9.6.2, Ecological Risk Assessment, fourth paragraph—Add at the end of the paragraph: "However, following the more general guidelines is usually more appropriate unless the site has been identified as a Superfund site."

Response: The team added the following sentence: "However, following the more general guidelines is usually more appropriate unless the site has been identified as required to do so by a regulatory program."

33. Page 119. Not sure why these USEPA documents are referenced in the style shown here—seems like they should be USEPA 1992, 1997, and 1998. I plugged the info into References, but they would need to be integrated with other citations to USEPA.

Response: Thank you for the corrections.

New York
Department of Environmental Control

34. There are two case studies from the same site in New York (Fort Edward Landfill). I suggest combining comments from the two project contacts into one case study.

Response: Case Studies #24 and #25, even though from similar locations or from the same site, represent different types of wetlands. Based on this, the team retains them as separate case studies.

35. The one photograph doesn't seem to justify having a "List of Photos." I suggest dong away with it.

Response: The photo has been removed

36. Section 2.3.2, the second and third sentences discuss hydrocarbon removal. Should this be moved to 2.3.3?

Response: Hydrocarbon removal has been changed to organic carbon removal in Section 2.3.2.

37. Section 2.3.3, the first three paragraphs describe what hydrocarbons are. I think these should be distilled to one or two sentences and get right into removal mechanisms. Most people know what hydrocarbons are.

Response: Most may know what hydrocarbons are; however, other comments we have received indicate that some people do not know what hydrocarbons are..

38. No need to call out Subsection 2.3.6.1. Omit numbering at this level.

Response: Thank you; the correction completed.

39. Figures 3-1 and 3-2 appear to be taken from another document. List source.

Response: The team member from New Jersey provided the unreferenced figures. We have added this credit fact below the figure descriptors.

40. Page 37, second paragraph—Suggest inserting "Properly designed and constructed" before first sentence.

Response: This same phrase could be added to most paragraphs throughout the document; however, we believe that this caveat is understood. We encourage proper design and proper construction in wetlands project, and for any other technique and have dedicated sections to both subjects.

41. Table 4-10—Vertically aligned headings are confusing (going both ways).
Response: We have changed all but the units column to horizontal.

42. Table 4-11—The shading is confusing.

Response: Thank you. We have removed the shading in the table boxes.

43. Page 46, first and second paragraphs—These examples lend themselves to highlight boxes instead of regular text.

Response: The team disagrees and chose to retain the formatting.

44. Section 4.5 uses mostly examples to describe remediation uses of wetlands. Should beef this up with a bit more theory/mechanisms and limitations.

Response: We have a section on mechanisms relative to particular groups of contaminants in Section 2.3. We have included advantages and limitations in Section 9.9. The team debated the organization of the document and considered two organization schemes: Organize the document on contaminant groups and discuss the application of regulatory authorities overseeing various contaminants in various circumstances, or organize around application and relevant regulatory programs and oversight. The latter was chosen since the team believes state and federal regulators are the primary users and the application scheme more clearly describes use of constructed wetlands. In the Executive Summary, we point out that this is not an innovative technology but there are innovative uses of a mature technology.

45. Section 5.2 goes on and on for 22 pages. It should be broken up into manageable sections or subsections for readability. Why does 5.2.4, Conceptual Design, come after 5.2.3, Mechanical Design? Needs to be better organized. Also, Section 5 should just be named Design, since Construction is covered in Section 6.

Response: We agree. The two sections have been switched, and the title has been modified.

46. Section 7.1 could use some subsection headings to better organize information.

Response: The team disagrees.

47. Table 7-2—List source of cost data.

Response: The sources of the cost data are included in the beginning paragraph of Section 7.1. Cost data for several of the tables are derived from these same sources of information.

48. Section 9.3—Provide link to nationwide Cooperative Extension Agencies http://www.reeusda.gov/1700/statepartners/usa.htm

Response: Thank you. It has been included.

49. A glossary is typically included as an appendix. Consider as an appendix.

Response: The team has chosen to leave it as Section 10 of the document to highlight its importance in this case.

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